Living and Fossil Calcareous Nannoplankton from the Australian Sector of the Southern Ocean: Implications for Paleoceanography

by

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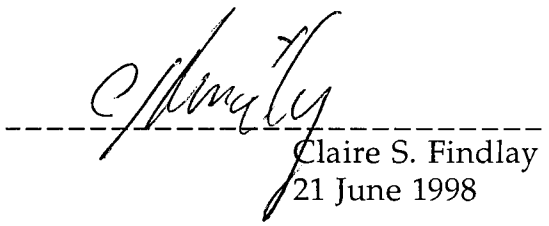
DECLARATION

This thesis contains no material which as been accepted for a degree or diploma by the University of Tasmania or any other institution, except by way of background information that is duly acknowledged. To the best of my knowledge and belief this thesis contains no material previously published or written by another person, except where due acknowledgment is made in the text.



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21 June 1998

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Abstract

This study documents the distribution of calcareous nannoplankton in the waters and surface sediments of the Australian Sector of the Southern Ocean, and applies the information to core samples from the region to infer past changes in the ocean between 41°S and 64°S. The preservation of calcite plates produced by these phytoplankton are preserved in pelagic sediments and are useful in paleoceanography.

Water column samples show that calcareous nannoplankton can be separated into five distinct assemblages associated with properties of the water mass, i.e., temperature, salinity, light and nutrients. In general the abundance and diversity of nannoplankton decrease poleward from subtropical to polar waters.

The surface sediments show an abundance and diversity of calcareous nannoplankton different from living assemblages in the water column. Surface sediments are dominated by a single assemblage including *C. pelagicus*, a species not found in water column samples. The absence of *C. pelagicus* suggests a recent extinction in the Southern Ocean. Of 45 surface sediment samples, only eight were identified as younger than 73 ka BP based on currently recognised biostratigraphy, indicating erosion and disturbance of sediments in the region. Preferential preservation of larger, more robust species of nannoplankton in the surface sediments suggests that chemical dissolution of calcite is significant.

Calcareous nannoplankton biostratigraphy from a 5.1-metre core (GC07; 45°S; 146°E; 3307m water depth), coupled with ^{14}C dates, oxygen isotope ratios and $\%CaCO_3$ data show that the core spans the interval of about 129 ky (from the beginning of the last interglacial) to Late Holocene. Changes in fossil assemblages with time are related to glacial and interglacial intervals, suggesting that the nannoplankton are useful as paleoclimatic

indicators. A change from dominance by *Gephyrocapsa muellerae* to dominance by *Emiliania huxleyi* occurred at about 11 ka BP, suggesting that the commonly used date for this reversal (73 ka BP) is not applicable for the Sub-Antarctic. The presence of Miocene and Pliocene species in the core samples indicates that reworking of sediments is common in the region.

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A. Objectives of this study

The aim of this project is to interpret the paleoceanography from the Australian Sector of the Southern Ocean using coccolithophorids as proxies. The first part of the project is to gain a sound understanding of the modern distribution of living coccolithophorids in this region. Water samples from the photic zone (surface to 200m) were collected between Australia and Antarctica to establish the diversity and abundance within this group of phytoplankton and to identify individual species and assemblages which may relate to hydrographic parameters including temperature, salinity, light and nutrients. Research on living calcareous nannoplankton in the Southern Ocean is limited (Hasle, 1960, 1969; Nishida 1979, 1986) and this study provides important new information as well as building on previous results.

Analysis of surface sediment samples from the same region determines how the living assemblages are preserved and the relationships among the living and fossil assemblages with overlying surface and subsurface water masses and hydrographic fronts. Controls of distribution of fossil assemblages include the degree of dissolution, which can be established by the presence or absence of more delicate species and the amount of malformation of coccoliths; and, the degree of erosion and reworking, identified by the presence or absence of extinct species and the extent of preferential sorting of the larger coccoliths. Seasonal and interannual productivity may also influence the surface sediment assemblage.

The final part of this project is the application of data from the living and surface sediment assemblages to downcore sediments (GC07), to determine the paleoceanography of the Late Quaternary in the Australian Sector of the Southern Ocean. Stratigraphy for the core samples is based on calcareous nannoplankton biostratigraphy supplemented by oxygen isotope data, $\%CaCO_3$ and ^{14}C dates. At present, biostratigraphic datum events for the Quaternary are based on calcareous nannoplankton from tropical to subtropical locations. One purpose of this study is to

determine the applicability of these datum events to subantarctic regions. Additionally, interpretation of paleoceanography and paleoclimate through changes in the calcareous nannoplankton assemblages downcore is considered. Of particular interest is the movement of oceanic fronts in this region, and the location of core GC07 should provide information on movements of the Subtropical Front through the Late Quaternary.

B. Coccolithophores

History

One of the more important historical events in the research of coccolithophores relating to this study, include the discoveries by Murray (1885) who established coccospheres as calcareous algae and recognised different habitats for different forms, e.g., rhabdospheres restricted to waters warmer than 18.3°C. In 1902 Lohmann (1902) recognised flagella as part of the coccosphere and proposed the term 'nannoplankton'.

Geological Record

Calcareous nannoplankton arose in the Late Triassic (Fig. 1) with the first true coccolith recognised within the Norian *Radocera suessi* ammonite Zone. Their appearance in the fossil record followed a period of heavy salt precipitation in the Tethyian Sea in the Permian and Triassic, and were most abundant during the Late Cretaceous when rising sea-levels led to marginal-sea deposits of chalk across much of northwest Europe (Houghton, 1993). These epicontinental seas had normal marine salinities (indicated by the presence of echinoderms and brachiopods), were warm and highly stratified, with estimated depths of between 50m to 200m (Houghton, 1993).

The late Cretaceous calcareous nannoplankton species were larger than their modern counterparts. At the Cretaceous/Tertiary boundary about 80% of species became extinct. Following the K/T boundary event there

was a radiation in the Palaeocene and early Eocene, followed by a further decline in the Late Oligocene (associated with ice development in the Antarctica) with a recovery in the Miocene (Young, 1994). Some extinctions occurred during the Pleistocene, including the discoasters, leaving the modern flora of 200 species. However, only 40 of these are found in the fossil record due to variable preservation, and difficulties associated with identifying the smaller coccoliths (Young, 1994).

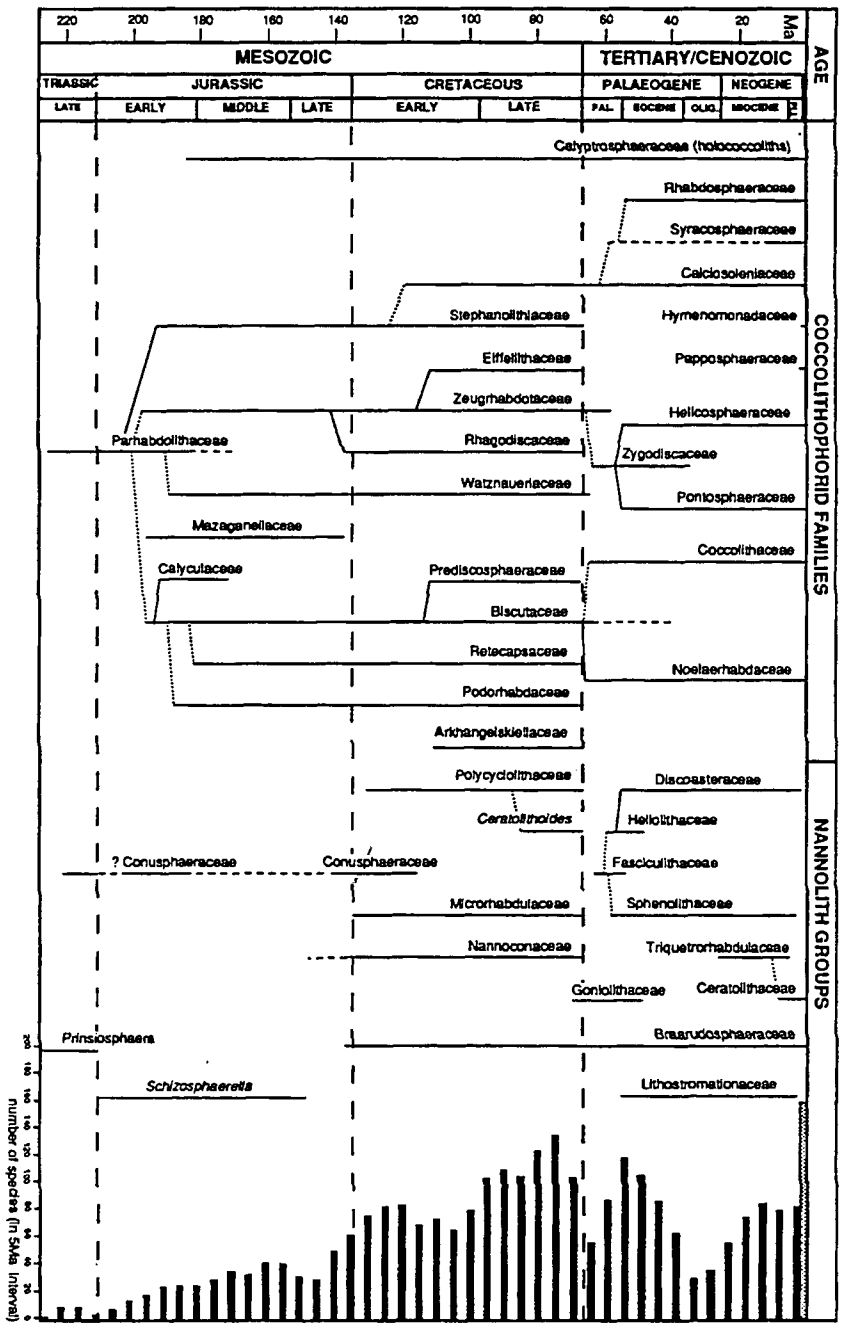


Fig. 1 Evolution of coccolithophorids depicting family level relationships from the Triassic to Pliocene (from Young, 1994).

Physiology

Calcareous nannoplankton are singled celled algae, known as coccospheres or coccolithophorids and are mainly phytoplankton living in the photic zone (upper 150m to 200m) of the oceans. Coccospheres produce an outer covering of individual calcite disks (coccoliths) which interlock to provide a protective layer to the cell. Individual coccospheres may produce multiple layers of coccoliths. The coccoliths are precipitated within the cell at a site attached to the golgi apparatus and are pushed to the outside of the cell. Upon death, these coccoliths separate, and are preserved in the sediments as individual disks.

Calcareous nannoplankton show a high degree of diversity in reproductive cycles (both vegetative and sexual), with motile and non-motile phases. The most familiar example of the bi-modal phase within a species is *Coccolithus pelagicus* which is found as a non-motile sphere of heterococcoliths (calcite crystals of different sizes and shapes) changing to a motile phase consisting of holococcoliths (calcite microcrystals of uniform size and shape) and a well defined haptonema. The motile phase (Plate; Fig. 1) is sometimes referred to as *C. pelagicus* f. *hyalinus*. Only the non-motile phase of heterococcoliths are preserved in the fossil assemblages. Changes in the life cycles may be brought about by changes in nitrogen supply (Klaveness and Paasche, 1979; Heimdal, 1993; Billard, 1994; Pienaar, 1994).

Morphology

There are a variety of shapes of coccoliths; the most abundant species, including *Emiliania huxleyi*, *Calcidiscus leptoporus*, *Coccolithus pelagicus* and *Gephyrocapsa* spp, produce placoliths. Placoliths are composed of two separate shields, the proximal shield adjacent to the cell wall, and the distal shield exposed to the outside environment. The two shields are joined by a central column. *E. huxleyi*, the dominant species in modern oceans, has a distal shield constructed of 'T' elements which

radiate from a central ring on the distal shield (Plate 1, Figs 1-3; see also Young et al. , 1997).

Different morphotypes of *E. huxleyi* have been recognised and although they are referred to in terms of temperature, i.e., 'warm water', 'cold water' and 'polar' form, more recent studies have indicated factors other than temperature control their distribution. For example, the 'warm water' and 'cold water' forms have been identified together in warm waters of the California Current (Winter, 1985). The 'polar' form has been recorded in warm waters north of the Subtropical Front, south of Africa (Verbeek, 1989). This form was previously considered to be restricted to subarctic waters where it was suggested nitrogen deficiency caused the malformation (Okada and Honjo, 1973).

Comparison of laboratory cultures and oceanic samples of *E. huxleyi* identified morphological variation of size, degree of calcification, malformation and genotypic variation (Young and Westbroek, 1991). Three types of genotypic variation of coccoliths were identified in oceanic samples: Type A ('warm water' form), the most common with heavier calcification and a central area forming a grill; Type B ('cold water' form) with a central area of lath-like elements and less calcified; and, Type C, a small coccolith with an open central area or covered with lath-like elements.

A number of species have a dimorphic endothecal covering, i.e., an outer layer of completely different coccoliths, e.g., *Syracosphaera pulchra*, *S. nodosa* and *S. anthos*.

Ecology

Coccolithophores exhibit distinct seasonal cycles with a great deal of regional variation (McIntyre and Bé, 1967; Samtleben et al., 1995a, 1995b). When conditions are optimal they can form monospecific blooms up to 50,000 km^2 in area (Blackburn and Cresswell, 1993). The requirements for

such blooms are thought to include concentrations of specific nutrients combined with suitable light and temperature although the exact cause of such blooms is not known (Moestrup, 1994). Production rates of individual coccospheres during optimal growth periods have been estimated at 2.5 divisions per day (Brand, 1994) with an estimated turnover of 4 to 10 days in temperate to tropical waters (Honjo, 1976). Standing stocks range from 10^7 - 10^8 per litre in the Norwegian Fjords (Winter et al., 1994), 115 x 10^6 in the coastal waters of Norway (Moestrup, 1994), and 10^4 to 3 x 10^5 in the Mediterranean Sea (Kleijne, 1991).

The most abundant species in the oceans today is *E. huxleyi*, a cosmopolitan species with a tolerance of temperatures between 2°C to 28°C (McIntyre and Bé, 1967). It is found in every ocean and sea and accounts for between 20% to 100% of the total coccolithophore community.

Malformation

Malformation, i.e., the incomplete formation of coccoliths, has been documented by a number of authors from marginal seas and open ocean environments (McIntyre and McIntyre, 1971; Berger, 1973a; Okada and Honjo, 1975; Nishida, 1979; Verbeek, 1989; Kleijne 1990; Giraudeau et al., 1993; this study). Malformation is recognised as either the affects of dissolution, or first order malformation due to nutrient deficiencies (Kleijne, 1990).

Malformed morphotypes of *E. huxleyi* are recognised as an important component of assemblages in the water column. Similar studies in the Australian region have reported malformation of *E. huxleyi* and *Gephyrocapsa oceanica* as frequent in the tropical waters of the Australasian region (Hallegraeff, 1984). In neritic environments of marginal seas of the Western Pacific, Indonesia and the Red Sea the majority of coccospheres were found to be malformed, possibly due to nitrogen deficiency (Okada and Honjo, 1975; Kleijne, 1990).

Malformation of *G. oceanica* and *C. pelagicus* has been identified in deep waters off Namibia (Giraudeau et al., 1993). This water body was found to be supersaturated with calcium carbonate indicating the malformation is not a result of dissolution. The malformed cells of *G. oceanica* were identical to those found in the Indonesian and China Seas (Okada and Honjo, 1975; Kleijne, 1990). Giraudeau et al. (1993) noted malformation occurred in nutrient-rich subsurface layers with high nitrate and phosphate concentrations and suggests the malformed population was transported into the area via intrusion of saline tropical water into the South Atlantic surface waters.

Vertical Transport and Preservation

Most surface sediment assemblages are found to closely resemble the living assemblages suggesting rapid vertical transport with little alteration between the two environments (Fig. 2).

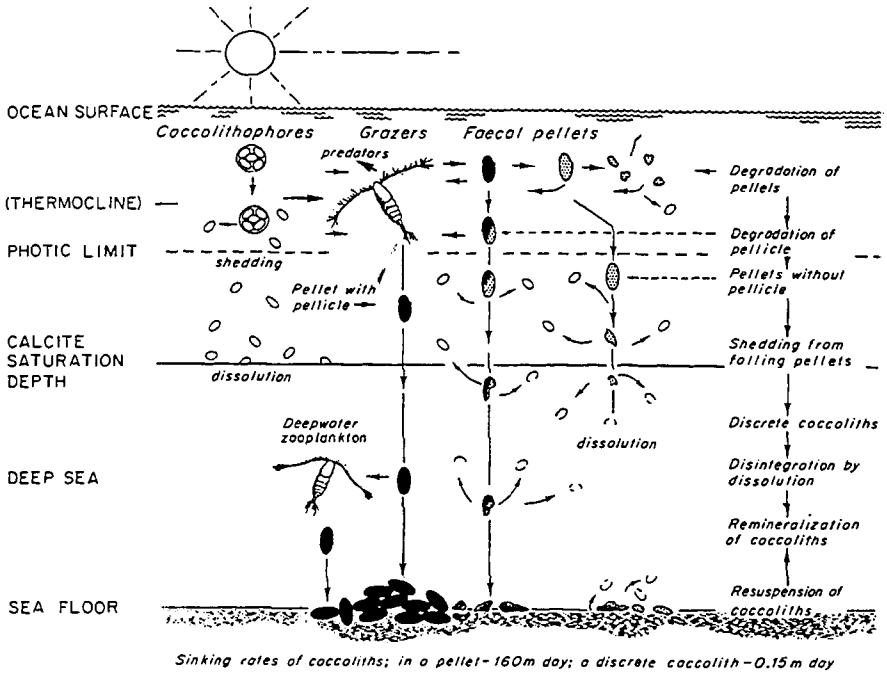


Fig. 2 Production, transportation, dissolution and sedimentation of coccoliths in the pelagic ocean (from Honjo, 1976).

The explanation for this accelerated sinking rate, compared to the estimate sinking rate of individual coccoliths of 100 years or more (from

the photic zone to the deep ocean), is the method of transport, i.e., incorporation in aggregates of fecal pellets or marine snow (Honjo, 1976).

Fecal pellets (Plate 1; Fig. 5) have an outer protective covering, the pellicle, which acts as a chemical barrier and smooths the surface, resulting in reduced drag and increased sinking velocity (Honjo, 1976). The average rate of settling for a fecal pellet has been estimated at 200m per day which is twice that of a marine snow aggregate and is considered to be the main form of transport in shallow waters (Steinmetz, 1994). In contrast, results from sediment traps show fecal pellets as 10% of the total flux in open oceans where marine snow is considered to be the major vehicle of transport, particularly at depth (Takahashi, 1994; Knappertsbusch and Brummer, 1995; Honjo, 1996).

In the Norwegian-Greenland Sea most coccoliths are transported via fecal pellets (Samtleben and Schröder, 1992), which vary in size and shape indicating a variety of zooplankton grazers. The compaction, size and form of fecal pellets influences their settling velocities. Disintegration depends on time in the water column, the stability of the fecal pellet, grazing of fecal pellets by other phytoplankton, and the process of coprorhexy (consumption of the outer membrane of the fecal pellet). The surface sediment record in the Norwegian-Greenland seas (Samtleben and Schröder, 1992) is characterised by high abundances of the most robust species, *C. pelagicus*, *E. huxleyi*, *G. muellerae* and *C. leptoporus*. In this region the main predators are copepods which produce loosely adhered fecal pellets which readily disintegrate in the water, thus leaving the most robust coccoliths as the main component of the sediment assemblage.

Investigations of the preservation of calcareous nannoplankton transported in fecal pellets in the North Atlantic found most coccoliths with little sign of etching and shields intact (Knappertsbusch and Brummer, 1995). The presence of ascidian spicules (i.e., aragonite, a less

stable form of $CaCO_3$ than calcite) in these fecal pellets confirmed good preservation.

Dissolution

Below the calcium carbonate compensation depth (CCD) preservation of calcareous nannoplankton are virtually non-existent within the carbonate free sediments. The CCD is the depth which separates calcium saturated water above from calcium depleted water below and lies at around 50% saturation. Above the CCD is the carbonate critical compensation depth (CCrD), the level below which calcium carbonate forms less than 10% of the sediment. The calcite lysocline lies above the CCrD and is the depth at which there is a significant decrease in calcite (Fig. 3). These three boundaries reflect the preservation of carbonates in the surface sediments. Factors affecting these boundaries include carbonate versus non-carbonate rain rates, biological productivity, water depth, pressure, turbulence and water chemistry; any of these factors may change the depth of the CCD .

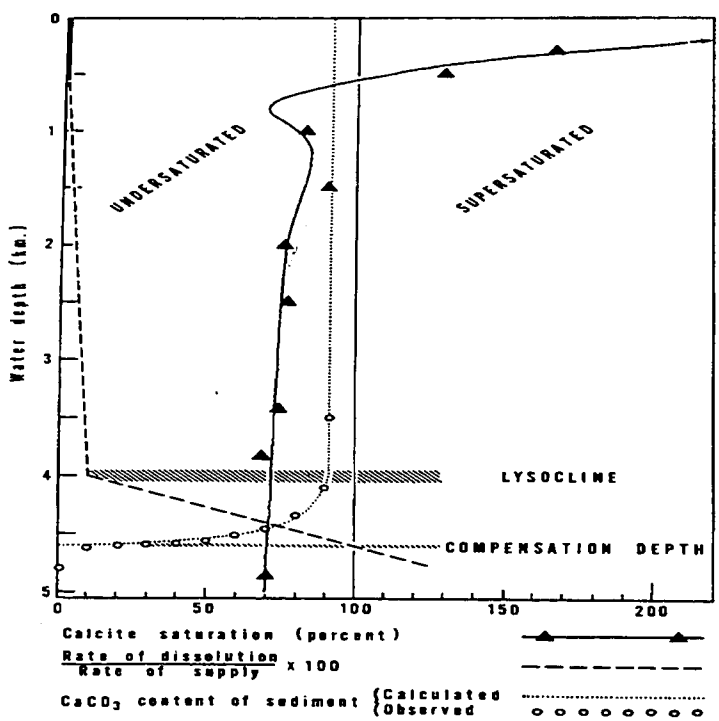


Fig. 3 Factors influencing the distribution of calcium carbonate in the equatorial Pacific sediment (from van Andel et al., 1975 *In* Kennett, 1982).

The average depth of the CCD lies at approximately 4500m, although, varies between oceans. In the Pacific Ocean the CCD is found at around 4000 to 4200m but has been recorded at 800m in the North Pacific Ocean and at 2000 in the South Pacific (Honjo, 1976 and references therein). Burns (1973) found the sediments below 4000m devoid of calcareous nannoplankton in the New Zealand region, indicating the CCD is above this depth. In the Atlantic the CCD is deeper, around 5000m or more. The shallower depths in the Pacific Ocean result from greater corrosiveness of bottoms waters due to their older age and greater amount of dissolved CO_2. Within the Southern Hemisphere the CCD depth is effected by the circulation of Antarctic Bottom Water, rich in dissolved CO_2 and low in carbonate ion concentrations, thus corrosive to calcium carbonate (Kennett, 1982).

More detailed studies on a regional basis have documented the calcite lysocline at approximately 3400m south of 45°S in the Southern Ocean (Takahashi et al., 1981). On the Southeast Indian Ridge the calcite lysocline has been estimated at 4300m (Howard and Prell, 1994). South of Western Australia the CCD is estimated at 4600m (Constans, 1975). In the Indian Ocean, between 40°S and 50°S, the CCrD was recorded at 4900m and the calcite lysocline between 4200-4300m; whereas, between 50°S and 60°S the CCrD was found at 3900m and the calcite lysocline between 3400-3500m (Kolla et al., 1976). The depth of the CCrD in the Indian Ocean is intermediate compared to the deeper depth in the Atlantic Ocean and the shallower depth in the Pacific Ocean (Kolla et al., 1976).

A number of these regional studies have found the position of these boundaries change through time. South of Western Australia, the CCD was found to vary in depth in high latitudes, with a depth of 3600m in the Lower Pliocene, reaching its present depth (4600m) in the upper Pliocene (Constans, 1975). In the Southern Ocean the lysocline is interpreted as shoaling during glacial stages (600m shallower during glacial stages 2 and 4, and 900m shallower during glacial stages 6 and 8) over the past 500 ka yr

BP, inferring lower carbonate ion concentrations during interglacial stages (Howard and Prell, 1994).

Although the CCD relates to the preservation/dissolution of coccoliths in the sediments, the preservation is more complex and can not be solely related to the carbonate chemistry of the surrounding seawater. The mode of transport, e.g., within a fecal pellet, also relates to the degree of dissolution. The interstial water within aggregates may differ from the surrounding waters, and may play a role in the preservation of coccoliths (Honjo, 1976).

Dissolution effects on calcareous nannoplankton have been documented by McIntyre and McIntyre (1971) who detailed preferential dissolution among species and noted this would cause a bias in the sediment assemblages, compared to the living assemblages. Berger (1973a) ranks 12 species in order of dissolution with *C. leptoporus*, *C. pelagicus* and *Gephyrocapsa* spp as the most resistant. The initial effect of dissolution on *C. leptoporus* is the breakage of the central connecting tube between the proximal and distal shields, and the ratio of separated versus non-separated shields of *C. leptoporus* can be used to determine the rate of $CaCO_3$ dissolution downcore (Matsuoka, 1990).

Bio-geochemical role

Calcareous nannoplankton play a major role in bio-geochemical cycling in the ocean and atmosphere. In particular, coccoliths are an important component of carbonate flux and play a major role in the oceanic exchange of CO_2 with the atmosphere. Some estimates of coccolith flux include 125-1180 X 10^6 m^{-2} d^{-1} individuals in tropical waters; 3400 X 10^6 m^{-2} d^{-1} at 4000m in the Japan Trench and the Panama Basin; and, 40 X 10^6 m^{-2} d^{-1} in the Norwegian Sea (Takahashi, 1994 and references therein).

More recently, calcareous nannoplankton have been linked to the production of dimethyl sulfide DMS and its precursor

dimethylsulphonioproionate (DMSP), where high readings have been found in association with high abundances of calcareous nannoplankton (Holligan et al., 1987; Turner et al., 1988). DMS is released into the atmosphere and is converted by oxidation to bi-products which act as nuclei for clouds (Fig. 4) thus increasing cloud albedo, or reflectivity, which plays a major role in the climate (Gibson et al., 1990).

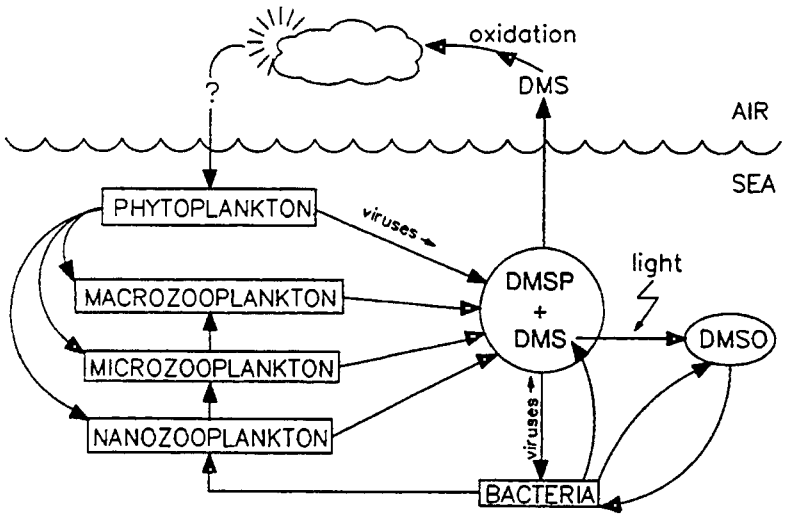


Fig. 4 Production of dimethyl sulfide (DMS) in the pelagic environment. DMSP - ßdimethylsulphoniopropionate; DMSO - dimethylsulfoxide (from Malin et al., 1994).

Increased sea surface temperature (SST) and light may increase DMS production, increasing cloud albedo which may act as a negative feedback mechanism in climate regulation (Malin et al., 1994).

C. Regional Oceanography

An understanding of the regional oceanography is essential for the interpretation of calcareous nannoplankton assemblages as the properties associated with separate water masses, i.e., temperature, salinity and nutrients, directly effect the assemblages. The boundaries between these separate water masses are often associated with oceanic fronts and the location of these fronts can define boundaries between assemblages.

The Southern Ocean, defined as the region south of the Subtropical Front (Fig. 5), comprises 20% of the world's ocean surface. The circulation of the

Southern Ocean effects all other oceans through inter-oceanic exchanges. Production of oxygenated surface water masses are incorporated into the Indian, Atlantic and Pacific Oceans at depth and contribute to creating the steady-state necessary for deep ocean circulation.

The Southern Ocean is dominated by the Antarctic Circumpolar Current (ACC) which flows in a continuous, eastward direction due to the prevailing winds. The Antarctic Circumpolar Current is considered to be the most voluminous current in the oceans today and extends almost to the bottom of the ocean, influencing the movement of more corrosive deep water masses in the Southern Ocean.

Zonation

The northern boundary of the Southern Ocean, although a little unclear in some places, e.g., between Tasmania and New Zealand, is defined as the northern limit of the Subtropical Front (STF) by most authors (Emery, 1977; Tchernia, 1980; Edwards and Emery, 1982; Belkin and Gordon, 1996).

The Southern Ocean is divided into three zones, the Subantarctic Zone between the STF and the SAF; the Polar Front Zone between the SAF and the PF; and, the Antarctic Zone between the PF and the Antarctic continent to the south (Emery, 1977). These zones (Fig. 5) are based on different surface water regimes identified by their unique properties of temperature, salinity and density.

Ocean Fronts

Fronts are areas of steep gradients in physical and chemical properties of the water, including temperature, salinity and density and are the locations of convergences or divergences. A divergence is an area where there is upwelling of water, i.e., the surface water is transported away and sub-surface water rises to take its place. The Antarctic Divergence is a wind-driven divergence. The effects of Ekman transport carry surface

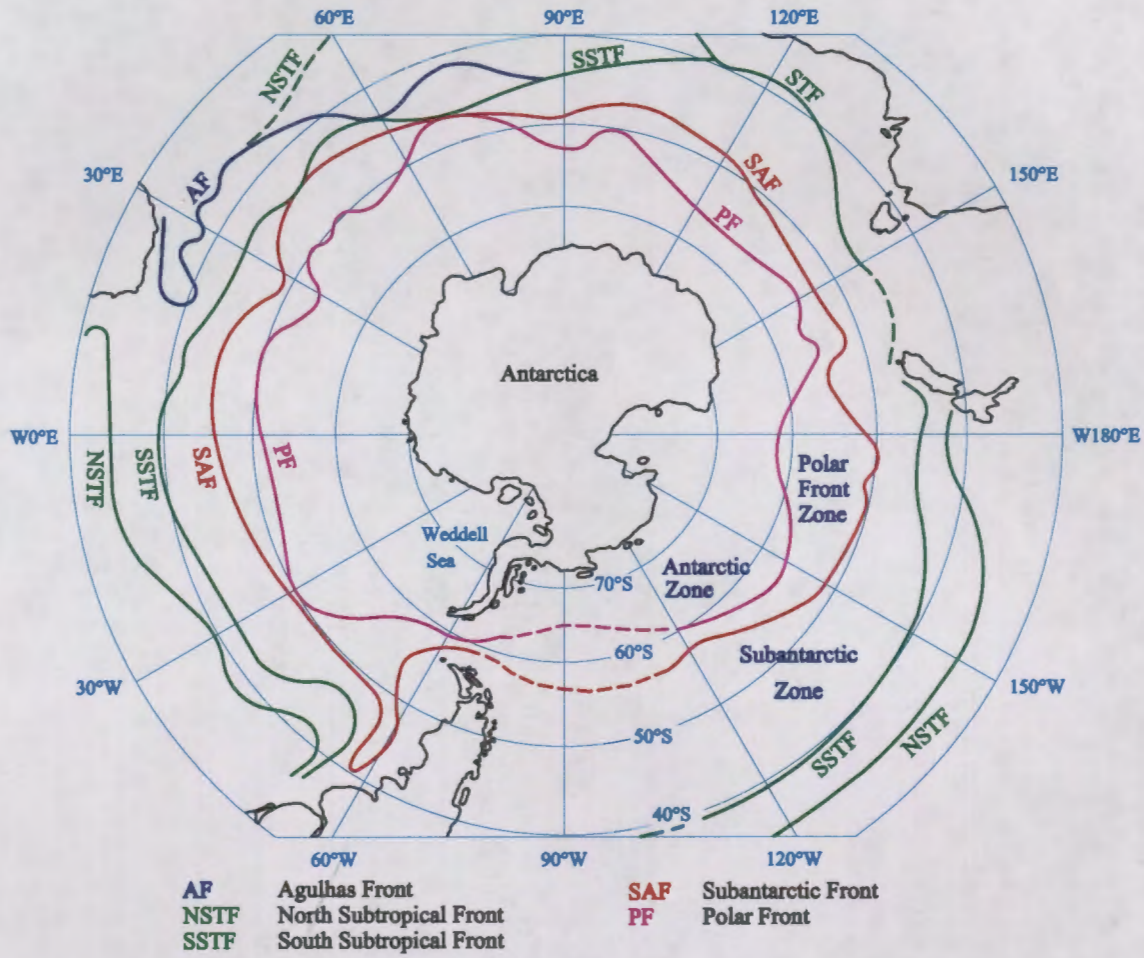


Fig. 5 Frontal positions and zones within the Southern Ocean (adapted from Belkin and Gordon, 1996 and Nowlin and Klinick, 1998).

waters equatorward north of the divergence due to west-prevailing winds and poleward south of the divergence due to east-prevailing winds.

Convergence zones, i.e., down-welling regions, are important locations of water mass formation, e.g., at the PF, the Antarctic Surface Water (ASW) travelling equatorward meets with the Subantarctic Surface Water (SASW) travelling poleward, and sinks to become the equatorward-flowing Antarctic Intermediate Water (AIW) in the Subantarctic and Polar Front zones (Fig. 6).

The location of frontal zones are dependent upon a number of factors including the topography of the ocean floor, the position of the continental masses, the influence of currents (e.g., the Agulhas Current) and wind fields. The fronts are often associated with eddies and meanders resulting in short-term changes in frontal positions (Gordon, 1971). These mesoscale meanders and eddies transport surface water masses and associated phytoplankton assemblages across frontal boundaries, e.g., a cyclonic eddy identified south of Australia carried ASW from the PF to the southern boundary of the Subtropical Front (Savchenko, et al., 1978).

The boundaries of fronts vary seasonally and interannually. Some fronts are more variable than others. Occasionally a single frontal system will temporarily split, forming a double frontal structure for a short time. The STF appears to be permanently divided into two separate fronts (Fig. 5) forming a double frontal structure in three locations (Belkin and Gordon, 1996).

Within the Australian Sector the three main fronts (STF, SAF and PF) are usually distinct, although confluence between the PF and SAF may occur (Belkin and Gordon, 1996). In this region (approximately 150°E), the STF and SAF are deflected poleward as a result of ocean-floor features including the Southeast Indian Ridge and the George V and Tasman Fracture Zones.

For the purposes of this research the definitions of fronts follow Belkin and Gordon (1996) and Rintoul et al. (1997). The data from Rintoul et al. (1997) was collected from the World Ocean Circulation Experiment (WOCE) section SR3, Marine Science Cruise AU9407, January 1994. This data was collected concurrently with filter samples used in this research project for the study of calcareous nannoplankton in the Southern Ocean, south of Australia.

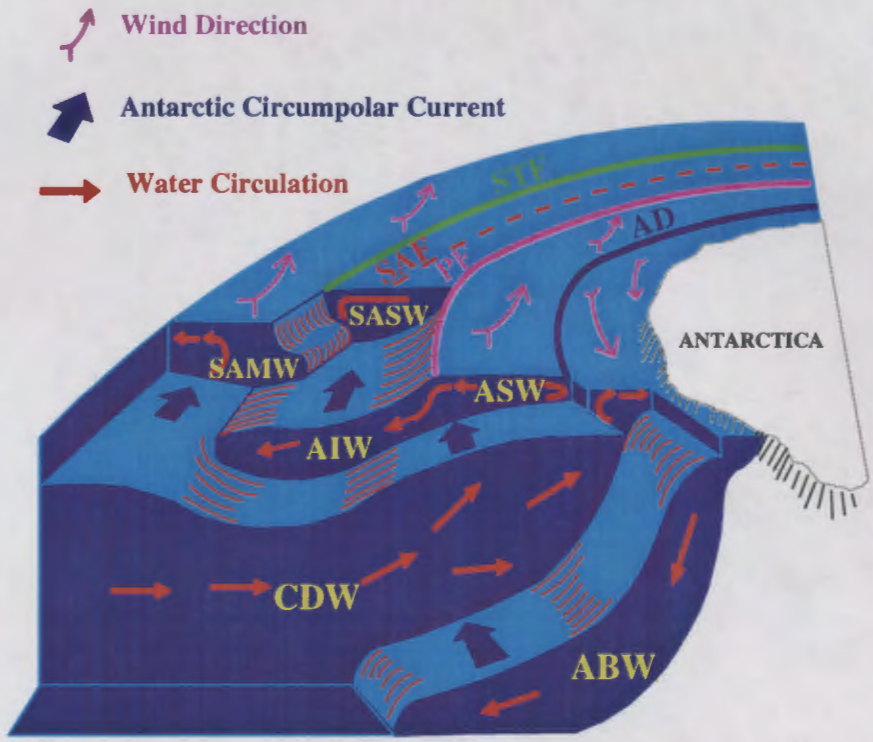
The Subtropical Front (STF)

The STF marks the boundary between warm, saline, subtropical waters to the north from colder, less saline waters to the south, separating subtropical to transitional assemblages of calcareous nannoplankton to the north, from transitional assemblages to the south. The term 'Subtropical Front' follows the terminology used by Belkin and Gordon (1996) and Rintoul et al. (1997); this front is also referred to as the Subtropical Convergence (STC). The STF zone is variable, complex and often indistinct in the Australian Sector.

The position the 12°C isotherm at 150m water depth with a surface expression of approximately 13°C (Fig. 7) identifies the STF at approximately 45°S to 46°S (Belkin and Gordon, 1996; Rintoul et al., 1997). Previous studies have located the STF south of Australia between 43°S and 44°S (Edwards and Emery, 1982), and 47°S during summer 1983-84 (Nishida, 1986).

The Subantarctic Front (SAF)

The definition of the SAF is the largest horizontal gradient in the temperature range of 3°C to 8°C at 300m water depth (Rintoul et al., 1997) which shows a surface expression of approximately 7°C to 9°C (Fig. 7). The structure of this front is variable, particularly the distance between the north (6-8°C isotherms) and south (3-6°C isotherms) boundaries. However, its position is relatively stable through time, unlike the STF.



SASW - Subantarctic surface water
SAMW - Subantarctic mode water
ASW - Antarctic surface water
AIW - Antarctic intermediate water
CDW - Circumpolar deep water
ABW - Antarctic bottom water

STF - Subtropical Front
SAF - Subantarctic Front
PF - Polar Front
AD - Antarctic Divergence

Fig. 6 Water Masses and associated fronts of the Southern Ocean (adapted from Hedgepeth, 1969).

Positions for this front have been previously recorded at 51°S (Edwards and Emery, 1982) and 49°S for summer 1983-84 (Nishida, 1986).

The Polar Front (PF)

This front is an area of down-welling where colder ASW sinks below warmer SASW and forms the Antarctic Intermediate Water (AIW). This convergence zone, also known as the Antarctic Convergence (Gard and Crux, 1991), varies in latitude between 47°S and 62°S (Belkin and Gordon, 1996).

The Polar Front is identified as the northern limit of the 2°C isotherm in the surface water during summer, at approximately 54°S for austral summer 1994 (Rintoul et al., 1997) with a surface expression of approximately 5°C (Fig. 7). The position of this front has been previously recorded at approximately 57°S south of Australia (Edwards and Emery, 1982).

Antarctic Divergence

The Antarctic Divergence is identified by the doming of isotherms (Fig. 7). At this location the poleward-flowing Circumpolar Deep Water (CDW) upwells from depths of 2000 to 4000m to approximately 150 to 200m (Tchernia, 1980). Rintoul et al. (1997) have placed this front at the at approximately 63°S for summer 1994, with a surface expression between the 0.5°C and 1°C isotherms (Fig. 7).

The poleward shift of the STF and the SAF south of Tasmania coupled with an equatorward shift of the PF (Edwards and Emery, 1982) places the PF and SAF in close proximity to each other. The same shift in position has been recorded before at approximately 147°E, interpreted as deflection related to the Tasman and the Balleny Fracture Zones (Belkin and Gordon, 1996).

Biogeographic significance of oceanic fronts

The location of the STF, SAF, PF and AD in the Australian Sector correlate with the boundaries between calcareous nannoplankton assemblages, defining separate biogeographic zones. The region to the north of the STF is recognised as a subtropical to transitional zone, between the STF and SAF a transitional zone, between the SAF and PF the subantarctic zone, and between the PF and AD, the antarctic zone.

Water Masses

Within the Southern Ocean there are a number of recognised separate water masses defined by their different properties including temperature, salinity and nutrients (Fig. 6). The surface and subsurface water masses directly effect the living calcareous nannoplankton assemblages, where the deeper water masses effect the preservation of coccoliths in underlying sediments.

In a poleward direction the surface water masses include, the Subantarctic Mode Water (SAMW) north of the STF; the Subantarctic Surface Water (SASW) between the STF and PF; and, the Antarctic Surface Water (ASW) south of the PF (Fig. 6). At depth three water masses are recognised, the Antarctic Intermediate Water (AIW), the Circumpolar Deep Water (CDW), and the Antarctic Bottom Water (ABW). The carbonate ion content of these deep water masses determines the degree of dissolution of coccoliths in underlying sediments and changes in bottom currents associated with the water masses can result in erosion of sediments. The definitions of the water masses are summarised below.

Subantarctic Mode Water (SAMW)

This surface water layer flows equatorward north of the STF (Fig. 6) and is characterised by a constant temperature. Edwards and Emery (1982) have suggested it is the body of water identified as the Subantarctic Upper Water (8-9°C) by Sverdrup et al. (1942). Passlow et al. (1997) identified this

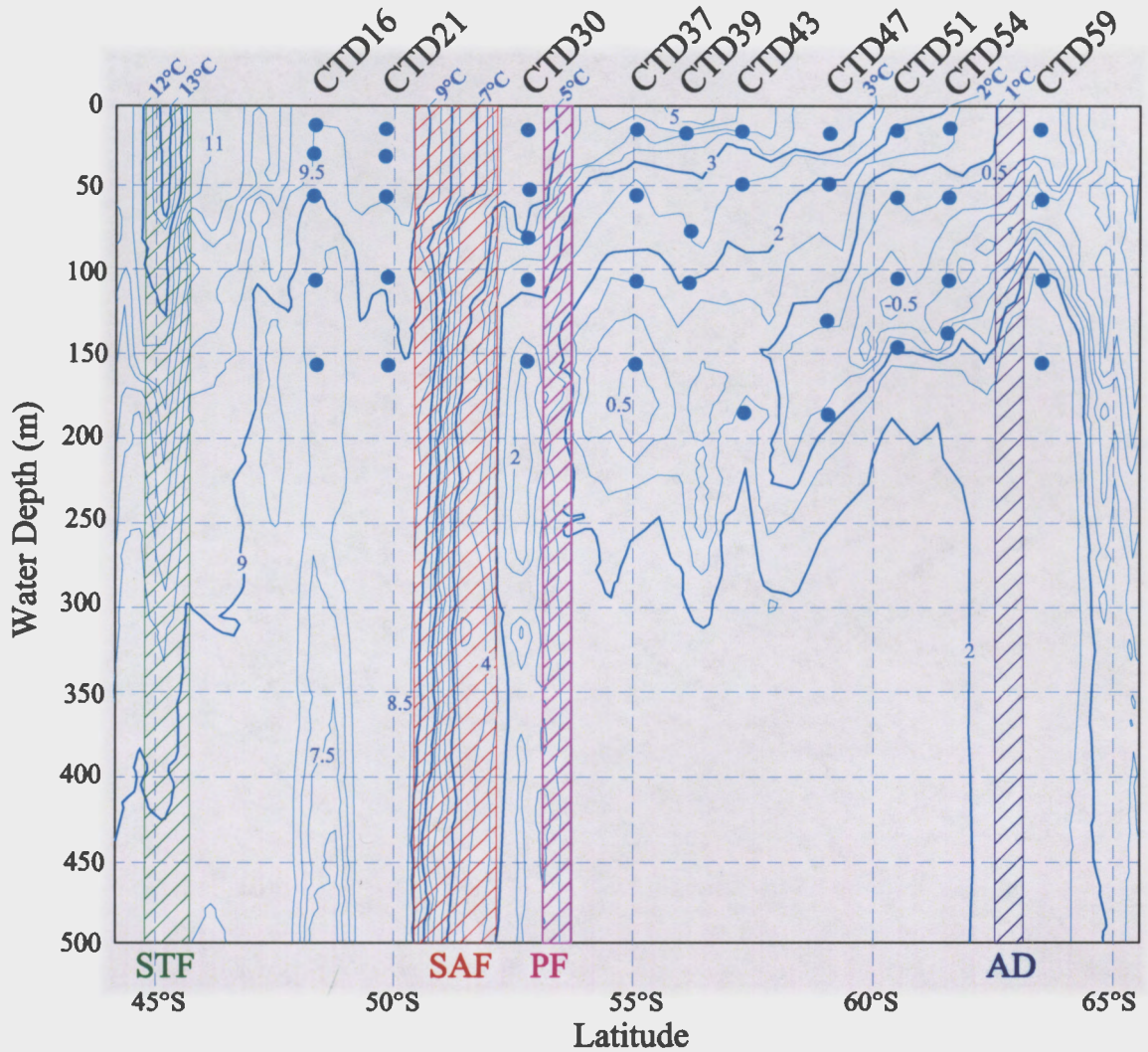


Fig. 7 Temperature profile of water column between Australia and Antarctica for February 1994. (Unsmoothed data from voyage V9407, based on Rintoul et. al. 1997.)

water mass south of Australia between 450-850m with a temperature range of 8-10°C and salinity of 34.5-34.6‰.

Subantarctic Surface Water (SASW)

This relative shallow surface layer flows equatorward between the PF and the STF (Fig. 6), above the SAMW, with a temperature above 3°C and more often, above 5°C (Gordon, 1971). The SASW occupies the Polar Frontal Zone, up to 500 km in width, and is interpreted as transitional between the SAMW north of the STF and the ASW south of the PF (Edwards and Emery, 1982).

Antarctic Surface Water (ASW)

The ASW is found between the Antarctic continent and the PF, is cold with temperatures ranging from -1.9-2°C, and is characterised by low salinity of 34.00-34.50‰ (Peterson and Whitworth, 1989). This surface water mass sinks at the PF to form the AIW at depth.

Antarctic Intermediate Water (AIW)

At depth, the AIW has been defined as a body of water with a temperature of 3-7°C and low salinity down to 1000m (Sverdrup et al., 1942). It is thought to originate at the PF, where the water is drawn down under the SASW and carried equatorward (Kennett, 1982). Passlow et al. (1997) have identified this water mass south of Australia with a temperature range of 4-8°C and salinity of 34.4‰ at a depth of 850-1100m.

Circumpolar Deep Water (CDW)

This water mass, also referred to as the North Atlantic Deep Water (NADW), is formed at the surface in the Norwegian and Greenland Seas, becomes dense, sinks and flows equatorward. It flows into the Southern Ocean from the north above the Antarctic Bottom Water to become an intermediate water mass in this region, where it upwells at the Antarctic Divergence (Fig. 6). The average temperature for this water mass is 0.5°C with a salinity of 34.68‰ (Sverdrup et al., 1942). The CDW has been divided into the upper CDW with a temperature range of 2.8-4°C and

salinity of 34.6‰ at depths of 1100-1600m; and, the lower CDW with a temperature range of 1.1-2.8°C and salinity of 34.72‰ between the depths of 1600-4000m (Passlow et al. 1997).

Antarctic Bottom Water (ABW)

The formation of this water is closely related to the formation of sea ice around the Antarctic continental margin where ice formation incorporates 30% of the salt from the water, adding the remainder to the water underneath which becomes denser and sinks. The ABW has been identified at 59°N in the Pacific (Kennett, 1982). The temperature of approximately -1.9°C and salinity of 34.62‰ identifies this water mass (Sverdrup et al., 1946), although more recently, the maximum temperature of 0°C is considered to reflect this water mass (Rintoul pers. comm.). In contrast, temperatures between 0.9-1.1°C and salinities between 34.70-34.72‰ at depths below 4000m have been referred to the ABW south of Australia (Passlow et al., 1997).

Chapter Two Literature Review

A. **Coccolithophorids in the Water Column**
   1. Diversity and abundance
   2. Morphotypes

B. **Coccolithophorids in Surface Sediments**

C. **Coccolithophorids in Deep Sea Cores**
   1. Stratigraphy
      a) Oxygen isotope stages
      b) Biostratigraphy of calcareous nannoplankton
   2. Previous studies relating to Quaternary cores in high latitudes
      a) Northern Hemisphere
      b) Southern Hemisphere
      c) Comparison of cores between the North and South Hemispheres

A. Coccolithophorids in the Water Column

Diversity and Abundance

Calcareous nannoplankton are abundant, diverse and widespread throughout the ocean. Floral assemblages of calcareous nannoplankton are distributed in biogeographic zones associated with changes in oceanic properties including temperature, salinity, light and nutrient levels. For example, McIntyre and Bé, (1967) identified four floral assemblages in surface waters of the Atlantic Ocean (Fig. 8).

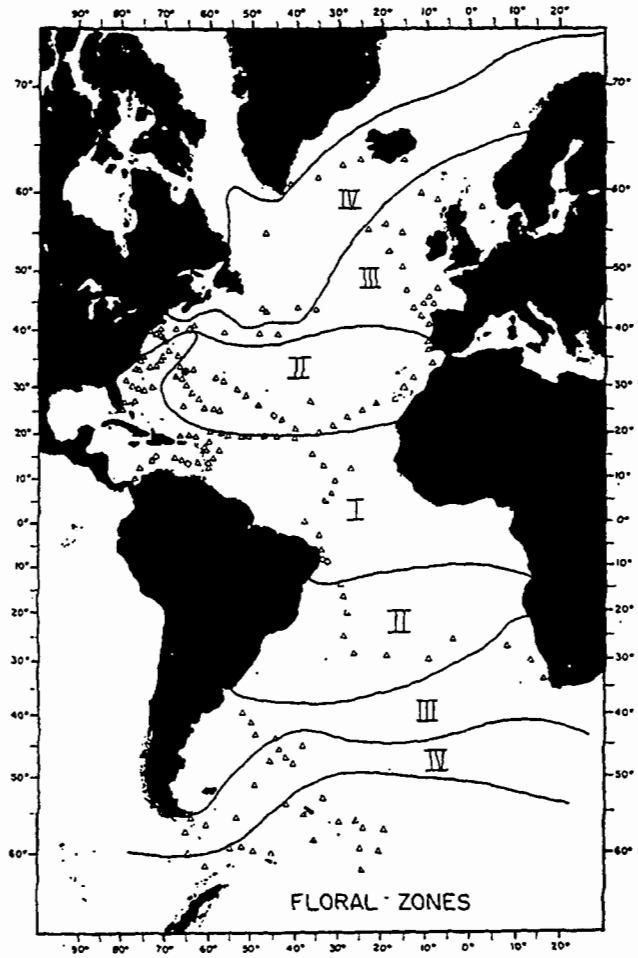


Fig. 8 Coccolithophorid floral zones of the Atlantic Ocean. I - tropical; II - subtropical; III - transitional; IV - subarctic-subantarctic (from McIntyre and Bé, 1967). Note the bi-polar nature of assemblage distributions.

This study (McIntyre and Bé, 1967) identified the minimum sea surface temperatures (SST) for a number of species, e.g., *G. ericsonii* (14°C); *U. tenuis*, *U. sibogae* and *R. clavigera* (16°C); *O. fragilis* (19°C); and *U. irregularis* (21°C). Overall abundance and diversity was at a minimum during July and August when SST were at a maximum, though *U. irregularis* increased in abundance during the same period. Other examples of seasonality include *C. pelagicus*, dominant in spring and summer, and *E. huxleyi* dominant in autumn and winter in subarctic to subtropical zones of the Atlantic (Okada and McIntyre, 1977, 1979).

Similarly, a number of studies in the Pacific Ocean have identified separate assemblages associated with individual water masses, e.g., subpolar waters, dominated by *E. huxleyi* 'cold water' form; temperate

waters with *G. caribbeanica, C. leptoporus* var. C; subtropical waters with *G. ericsonii, R. clavigera, U. tenuis* and *D. tubifera;* and, tropical waters with *U. irregularis, G. oceanica* and *C. leptoporus* var. B (McIntyre et al., 1970).

In the North Pacific six floral zones were identified (Fig. 9), the subarctic zone, dominated by *E. huxleyi* 'subarctic' form; the transitional zone dominated by *E. huxleyi* 'cold water' form and *R. clavigera;* the central zones by *U. irregularis;* and, the equatorial zones by *G. oceanica, C. leptoporus,* and O. *fragilis.* Vertical preference was recorded for *U. irregularis* and *R. clavigera* in the upper photic zone, *U. tenuis* and *O. fragilis* in the middle euphotic zone, and *F. profunda* and *T. flabellata* in the lower photic zone (Okada and Honjo, 1973).

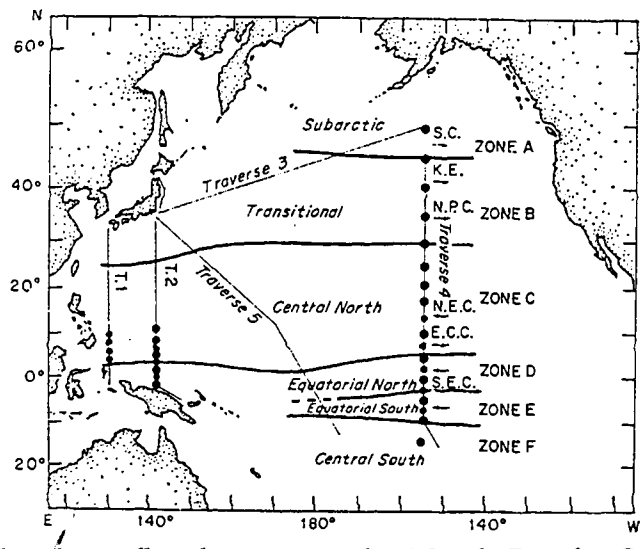


Fig. 9 Coccolithophore floral zones in the North Pacific Ocean (from Okada and Honjo, 1973).

In the Pacific differences in vertical distribution occur with highest densities between 25-55m in the equatorial zone and between 0-100m in the subtropical zone, with an overall decrease in surface waters from north to south and an increase at the equator. In the mid-Pacific, high abundance were found down to 30m and between 50-100m in the transitional zone (Honjo and Okada, 1974). Within the Kuroshio Current (31°N) adjacent to Japan, *E. huxleyi* was shown to dominate down to 100m where it is replaced by *G. oceanica,* which may indicate the boundary of this cold water mass (Nishida, 1979).

In the Norwegian-Greenland Sea three separate assemblages were associated with three water masses showing strong seasonal variation in temperature, light intensity, nutrients and currents (Samtleben et al., 1995a, 1995b).

In the Indonesian region with high SST, few calcareous nannoplankton were found (though diatoms were abundant, contrary to the common belief that calcareous nannoplankton prefer warm water and diatoms prefer cold water or upwelled waters (Kleijne, 1991)). South of Africa floral assemblages were associated with subtropical, subantarctic, polar and antarctic waters (Verbeek, 1989; Eynaud et al., in press).

In the Southern Benguela system a transect from an upwelling zone, across an upwelling frontal zone, through a mixed zone (zone of mixing between oceanic and aged upwelled water), across the offshore zone, into the oceanic zone (Fig. 10) identified five separate assemblages associated with five biogeographic zones (Giraudeau and Bailey, 1995). Highest cell densities were recorded in the upwelling zone indicating active upwelling conditions are favourable to coccosphere production.

In contrast, an earlier study in the same region found highest densities associated with low concentrations of inorganic nutrients following a relaxation of upwelling conditions, i.e., calcareous nannoplankton were dominant over diatoms and dinoflagellates in stable stratified water with low nutrients, particularly nitrate (Giraudeau et al., 1993). In the same study *C. pelagicus* was identified as a common component of the cold upwelling water of the Southern Benguela System.

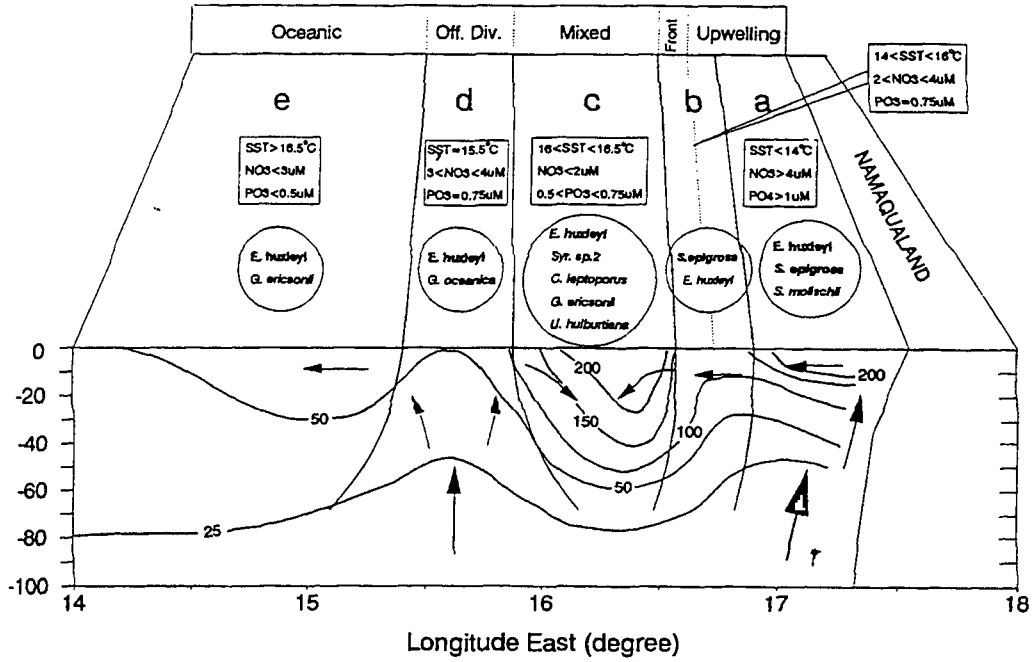


Fig. 10 Coccolithophorid zones (a-e) identified in the Southern Benguela System. Vertical contours - number of coccolithophores per litre of water ($x10^3$ cells l^{-1}); arrow - inferred circulation; SST - sea surface temperature (from Giraudeau and Bailey, 1995).

Within the Australian region highest cell densities were found between 50m and 75m at oceanic stations and between 10m and 40m at coastal stations, with *G. oceanica* dominant in tropical waters (Hallegraeff, 1984). South of Australia, diversity of coccolithophores varied from absent to five species south of the Subtropical Front (Hasle, 1960, 1969). Three calcareous nannoplankton assemblages have been identified in the same region between 44°S and 64°S, i.e., subtropical, subantarctic and antarctic assemblages (Nishida, 1986).

Morphotypes

Two morphotypes of *C. leptoporus* were identified in the Pacific Ocean, variety C with an average of 20 elements on the distal shield of the coccolith restricted to warm subpolar waters with a SST minimum of 8°C; and, variety B with an average of 30 elements preferring tropical to subtropical waters with a SST minimum of 18°C (McIntyre et al., 1970). In the Australian region a small variety of *C. leptoporus* was identified north of the Subtropical Front and is considered to be restricted by the

13°C isotherm, with a larger form found south of the Subtropical Front (Hiramatsu and De Deckker, 1996).

Three morphotypes of *E. huxleyi* have been identified: a 'warm water' form, heavily calcified with a grill-like structure covering the centre of the coccolith and 'T' elements on the distal shield joined; a 'cold water' form, lightly calcified with a central area open or covered in lath-like elements; and a 'polar', or 'subantarctic' form with distorted 'T' elements (Verbeek, 1989; McIntyre and Bé, 1967; Okada and Honjo, 1973; van Bleijswijk et al., 1991; Hiramatsu and De Deckker, 1996). In the Pacific Ocean assemblage zones have been defined based on these morphotypes, the subantarctic zone with the 'subantarctic' form, and the transitional zone with the 'cold water' form (Okada and Honjo, 1973). In the South Atlantic only the 'cold water' form was identified to 65°S (McIntyre and Bé, 1967). Both 'warm water' and 'cold water' forms have been identified in warm waters (Winter, 1985; Verbeek, 1989; Hiramatsu and De Deckker, 1996; this study), suggesting these morphotypes are not entirely temperature dependent although some studies consider the distribution of the 'warm water' form is controlled by temperature whereas the 'cold water' form is not (Verbeek, 1989).

It has been suggested malformation of *E. huxleyi*, producing the 'polar' or 'subantarctic' form, is first order malformation resulting from nutrient deficiency or temperature (Okada and Honjo, 1973; Kleijne, 1990; Brown and Yoder, 1993; Giraudeau et al., 1993). More recently, it has been described as second order malformation due to dissolution (Young, 1992). Similarly, malformation of *G. oceanica* in the marginal seas of the Western Pacific Ocean and Red Sea are considered to reflect variations in nutrients (Okada and Honjo, 1975).

Intra-specific variation of coccoliths have been recorded within cultured strains of *E. huxleyi* and compared to oceanic populations, identifying five strains based on degree of completion, size, degree of calcification, malformation and genotypic variation. The results showed distal shield

and central area elements, combined with size, as the only effective parameters to identify types. Of the types identified, Type A was common in oceanic populations, Type B rare, and Type C correlates with the 'cold water' form (Young and Westbroek, 1991).

B. Coccolithophorids in Surface Sediments

A number of studies have identified biogeographic zones based on assemblages in surface sediments which are associated with physico-chemical properties of overlying water masses. In the southwest Indian Ocean *G. oceanica* dominated the inner shelf environment, *E. huxleyi* the Agulhas Current region and *G. oceanica* and *C. leptoporus* the deep water region (Fincham and Winter, 1989). *C. leptoporus* increased poleward along with increases in nutrient levels, particularly phosphate, although the increases are considered to reflect its resistance to dissolution. Increases in abundance of *G. oceanica* and *H. carteri* are associated with high nutrient levels.

In surface sediments beneath the Benguela System, middle to outer-shelf and slope environments of warm waters were dominated by *G. oceanica;* cool, low salinity waters of the shelf dominated by *H. carteri* (with a minor component of *S. pulchra*); the upper and lower slope environments dominated by *C. leptoporus* (with a minor component of *U. sibogae*); and, upwelling zones dominated by *C. pelagicus* (Giraudeau and Rogers, 1994).

In coastal areas of southeast Japan *G. oceanica* dominated surface sediments, due to its tolerance for low salinity (Okada, 1992). Comparisons between water-depth and individual species in surface sediments identified *G. oceanica, G. ericsonii, Helicosphaera* spp and *Syracosphaera* spp preferring shallower neritic environments, and *C. leptoporus, U. tenuis, E. huxleyi* and *U. sibogae* preferring deeper waters of the pelagic environment.

Distribution of coccoliths in surface sediments of marginal seas in the North Sea are attributed to spatial and temporal changes in the populations of phytoplankton in overlying waters and the degree of stratification of the those waters (Houghton, 1988). Diatoms dominated the weakly stratified, well-mixed waters whereas calcareous nannoplankton dominated the stratified, nutrient-poor surface waters (Fig. 11). A reduction in abundance and diversity of calcareous nannoplankton in surface sediments between outer continental shelf environments to inner shelf environment was found (Houghton, 1988, 1993).

In the Norwegian-Greenland Sea biogeographic zones in surface sediments correlate to living assemblages and overlying surface water masses (Eide, 1990; Samtleben et al., 1995b; Fig. 12).

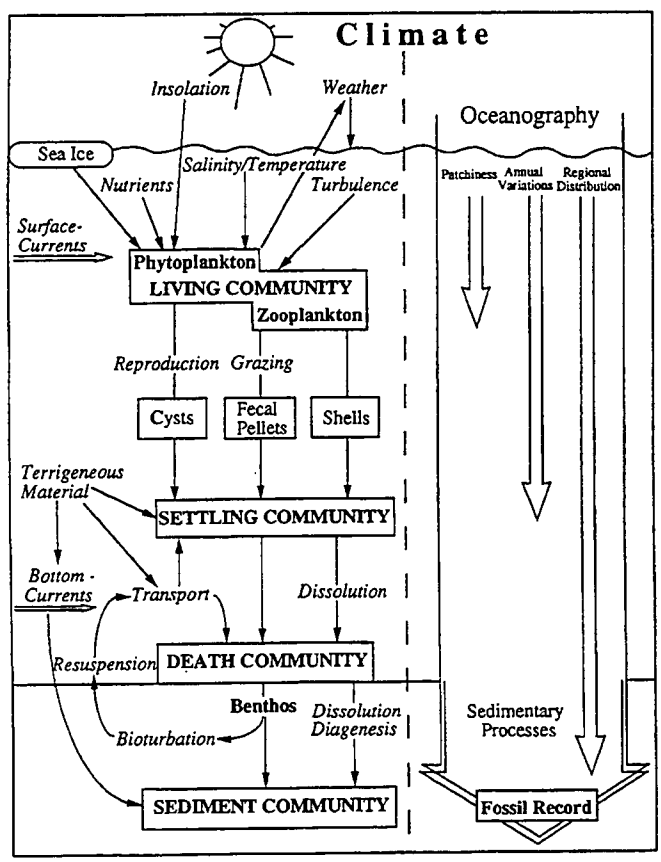


Fig. 12 Factors influencing the establishment of the fossil record of phytoplankton and the estimated content (spatio-temporal) from the same record (from Samtleben et al., 1995b)

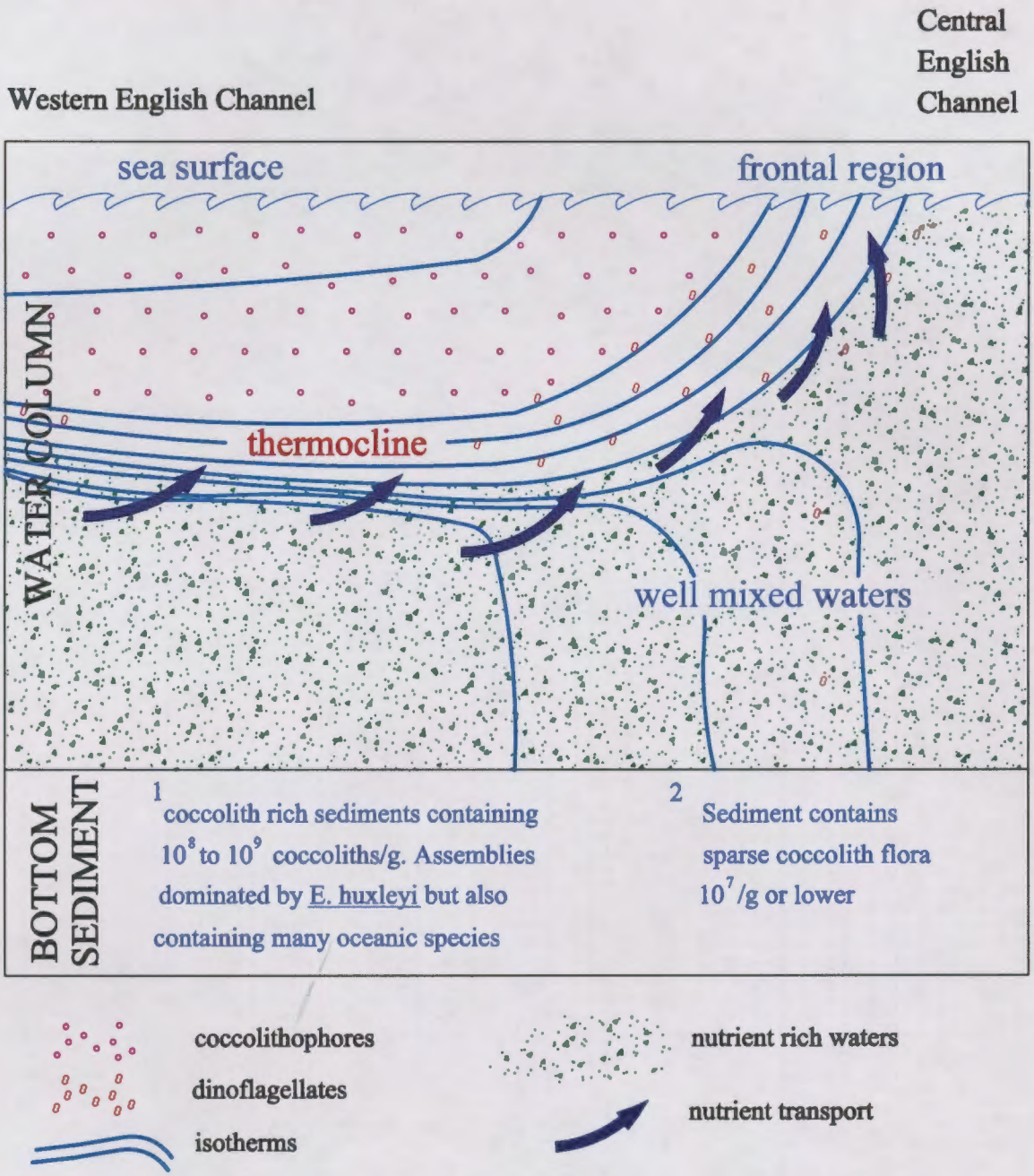


Fig. 11 Representation of the spatial distribution of coccoliths in the frontal region of the English Channel during summer (from Houghton, 1988).

In contrast, factors affecting sedimentation, including vertical flux in fecal pellets and varying carbonate dissolution of different water masses, were found to obscure the original living assemblages in the same region (Samtleben and Schröder, 1992). Four main species were recorded in the surface sediments, *E. huxleyi*, *C. pelagicus* and to a lesser degree, *C. leptoporus* and *G. muellerae*, which are rare in the living assemblage. The preferential preservation of these species results in a different sediment assemblage, where the domination by *E. huxleyi* and *C. pelagicus* reflects dissolution rather than a cold-water assemblage for the surface waters above.

Surface sediment data for the Pacific is considered to reflect rates of dissolution and destruction rather than biogeographic distribution, as sedimentation rate is low and longer resident time of sediments obscures the living biogeographic distribution (McIntyre et al., 1970). Although some studies have related surface sediment assemblages to individual water masses where it is considered preservation processes do not alter the assemblage between the living environment and surface sediments (Gietzenauer et al., 1976). In the Australian region, geographic distribution of coccolithophorids in surface sediments have been related to SST in the Tasman and Coral Seas, particularly *C. leptoporus*, *E. huxleyi* and *F. profunda* (Hiramatsu and De Deckker, 1997a). In the New Zealand region four biogeographic zones were identified based on assemblages in surface sediments, considered to reflect present-day hydrology (Burns, 1973). In the same region, separate assemblages were identified in surface sediments for the shelf region, the slope, the continental rise and the basin environment (Burns, 1975a). Differences in dissolution, abundance and diversity were recognised between the assemblages. Three coccolithophore groups were noted, a small coccolith group found in all assemblages, a group dominated by *G. oceanica* in higher proportions in the shelf environment, and a large coccolith group with low percentages in the shelf, increasing toward the basin.

Throughout the Atlantic Ocean eight species showed different biogeographic zones between the water column and the surface sediments (McIntyre and Bé, 1967). This is interpreted, in part. as the migration of these species to their present (living) boundaries in the last 12 ka yr BP ('ka yr BP' hereafter referred to as 'ka') due to the Atlantic Ocean's warming since the Last Glacial Maximum (LGM); with warm-water species were located approximately 15° in latitude more equatorward in the North Atlantic prior to 10 ka, compared to their present-day position. For example, *D. tubifera*, abundant in water samples in the North and South Atlantic, is common only in the surface sediments of the South Atlantic, suggesting it re-colonized the North Atlantic after the LGM at 12 ka.

In the same study (McIntyre and Bé, 1967) *C. pelagicus* showed a much wider distribution in the surface sediments (identified in all biogeographic zones including high latitudes of the Southern Ocean) compared to the water column. The surface sediments are post-glacial, less than 12 ka, indicating the disappearance of *C. pelagicus* from the Southern Hemisphere in recent times. This is explained in part by the post-glacial migration poleward of subtropical water into present subpolar waters of the Southern Ocean, resulting in regional extinction. The ecological niche of *C. pelagicus* species is considered to have been restricted to transitional waters, a narrow region between subtropical and subpolar waters. Oxygen isotope records show a warming at around 8 ka (McIntyre et al., 1970 and reference therein) which would support the hypothesis of an extinction event for this species in its already restricted environment in the Southern Hemisphere. Thus the surface sediment record in part reflects past populations rather than present-day surface water populations.

C. Coccolithophorids in Deep-Sea Cores

Calcareous nannoplankton play a key role in deep-sea biostratigraphy. Combined with other stratigraphic indicators, such as $\delta^{18}O$, calcareous nannoplankton provide reliable dating. In addition, variation in calcareous nannoplankton assemblages may be used to interpret regional paleoceanography. Variation in assemblages in downcore sequences can be correlated to interglacial and glacial cycles and associated changes in surface water masses and positions of oceanic fronts.

Stratigraphy

Oxygen isotope stages

The calcareous shells of marine organisms incorporate stable isotopes of oxygen during their construction. Initial work by Emiliani (1955) carried out on planktonic foraminifera showed that $\delta^{18}O$ (the ratio between the stable oxygen isotopes ^{18}O and ^{16}O) in calcium carbonate varies according to temperature and $\delta^{18}O$ of seawater. To the extent that ^{18}O reflects water, the ratio can be used as an index of global ice volume. ^{18}O is enriched in the oceans during periods of ice growth when ^{16}O is transferred via the atmosphere and stored within the ice sheets on land. Conversely, during periods of melting, ^{16}O is transported back to the oceans. Thus, the $\delta^{18}O$ record from any given deep-sea core sequence is a record of changes in global ice volume and local temperature (Shackleton and Opdyke, 1973, 1976; Pisias et al., 1984; Prell et al, 1986).

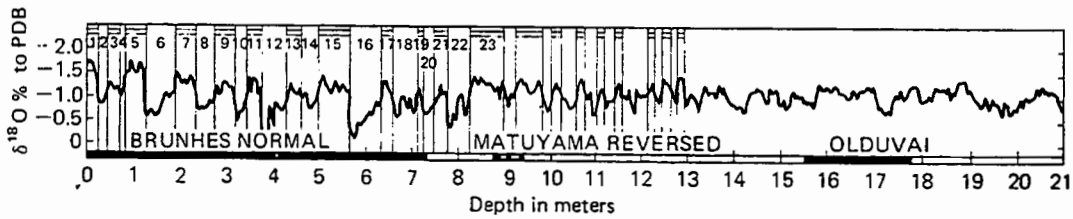


Fig. 13 Oxygen isotope stages and magnetic reversal from core V28-239 (from Emiliani, 1955, 1966; Shackleton and Opdyke, 1976 *In* Kennett, 1982).

Early studies established 23 oxygen isotopic stages (Emiliani, 1955, 1966; Shackleton and Opdyke, 1973, 1976) extending from present day to the Jaramillo magnetic reversal event (Fig. 13), although many more are now known. Oxygen isotope stratigraphy commonly labels warm (interglacial) intervals with odd numbers and cool (glacial) intervals with even numbers. A detailed study of the last 300 ka (Martinson et al., 1987; Pisias et al., 1984), subdivides the most recent eight stages into separate substages (Fig. 14). The interpretation of oxygen isotope stages based on $\delta^{18}O$ data remains ambiguous unless supported by additional data such as carbon isotope dating, carbonate curves and/or biostratigraphy.

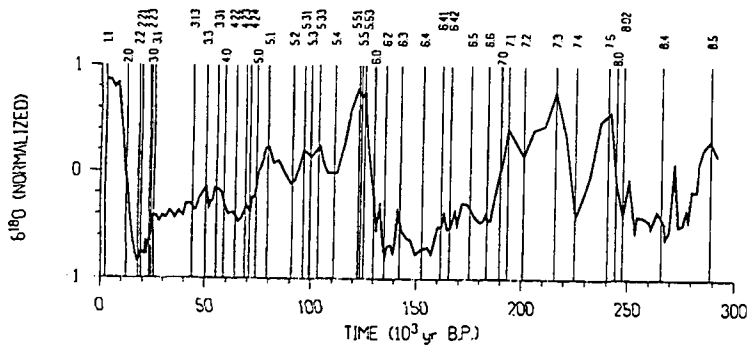


Fig. 14 Oxygen isotope stages based on Pisias et al., 1984 (from Martinson et al., 1987).

Biostratigraphy of calcareous nannoplankton

The most widely adopted biostratigraphic zonation schemes for calcareous nannoplankton are those by Martini (1971), who divides the geological record into nannoplankton zones (NN) with various datum events separating the zones; and Okada and Bukry (1980), who use the divisions of calcareous nannoplankton zones (CN) which defines additional zones. Figure 15 illustrates these different zonations schemes for the Neogene. The boundary of the Pliocene-Pleistocene is identified by the LO of *Discoaster brouweri.* However, data from subantarctic cores show this genus is absent, resulting in difficulties defining this boundary in the subantarctic (Geitzenauer and Huddlestun, 1972).

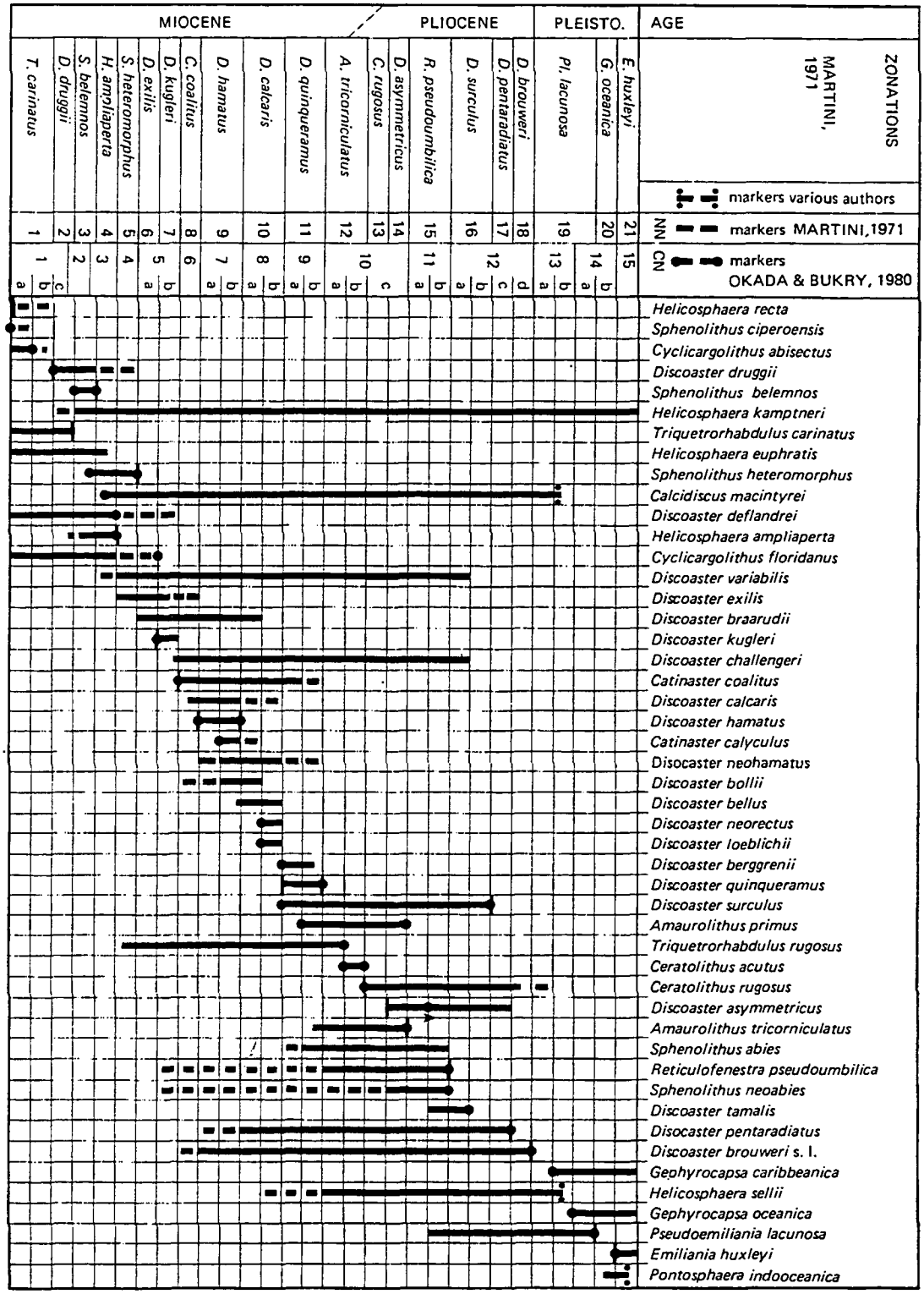


Fig. 15 Distribution of zonal markers and other species in the Neogene (from Perch-Nielsen, 1985).

The CN and NN zonations are of limited use for the Quaternary period where it is necessary to use additional sources for biostratigraphic definitions.

Two calcareous nannoplankton biostratigraphic datum events established by Gartner (1977) are important for the Quaternary: the last appearance (LO) of *Pseudoemiliania lacunosa* in stage 12 and the first appearance (FO) of *Emiliania huxleyi* in stage 8. Thierstein et al., (1977) established these two datum events as globally synchronous with the LO of *P. lacunosa* in the middle of stage 12 (458 ka), and the FO of *E. huxleyi* in late stage 8 (268 ka), with a third datum event recognised as the reversal in dominance between *G. caribbeanica* and *E. huxleyi*. The *G. caribbeanica-E. huxleyi* reversal event was found to be time transgressive, occurring in tropical waters in stages 5a and 5b (85 ka) and in transitional waters during stage 4 (73 ka).

Acme zones are also used biostratigraphically to approximate the age of sediments. An acme zone marks the dominance of one species over a short time interval. The term 'acme' is also used by some authors to describe the highest abundance of a species in a core, although not necessarily dominant over other species. In this study the first interpretation of 'acme' is adopted, i.e., where one species is dominant over all others. For oxygen isotope stages 1 to 12 Weaver (1993) defined four acme zones based on the acme of individual species (Fig. 16).

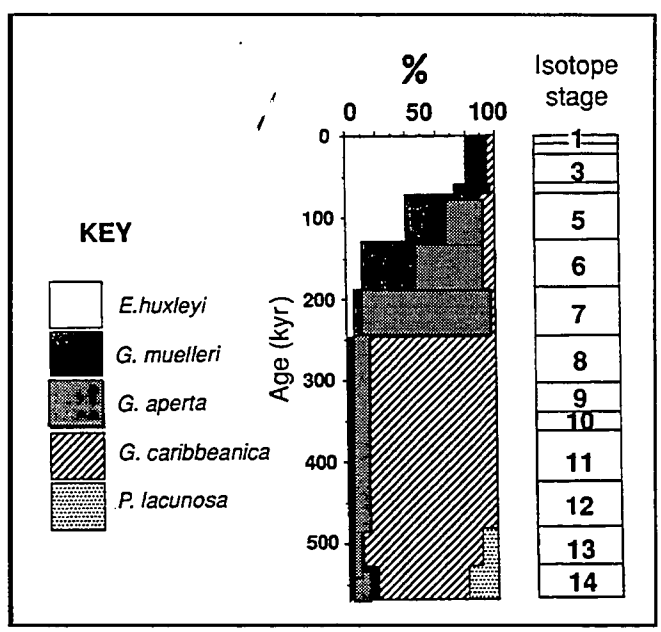


Fig. 16 Stratigraphical distribution of the dominant nannofossil species in the sediments of the Madeira Abyssal Plain off northwest Africa (from Weaver and Thomson, 1993).

Acme zones are useful where established datum events are difficult to detect. For example, *E. huxleyi* occurs late in stage 7 in low numbers, with a slight increase at the boundary of stages 6 and 7, and again at the boundary of stages 5 and 6. However, it does not reach high abundance (50% or more of the assemblage) until stage 4. Thus its FO in stage 7 is difficult to reliably detect. The termination of the acme zone for *G. caribbeanica*, at the boundary of stages 7 and 8 (Weaver and Thomson, 1993) can be used as an indication of where to look for the FO of *E. huxleyi*.

Beaufort and Giraudeau (unpublished data) have listed four significant acme zones in the North Atlantic based in part on previous publications (Pujos, 1988; Weaver, 1993):

1.	acme zone of *Emiliania huxleyi*	stages 1 to 3
2.	acme zone of *Gephyrocapsa muellerae*	during stage 5
3.	acme of small *Gephyrocapsa* spp	during stages 6 to 8
4.	acme of *Gephyrocapsa caribbeanica*	during stages 9 to 15

As the identification and classification of *Gephyrocapsa* spp is somewhat obscure in the literature, particularly with regard to the small varieties (*G. aperta* and *G. pelta*. Beaufort and Giraudeau (unpub.) refer to the *G. aperta* acme of Weaver and Thomson (1993) as 'small *Gephyrocapsa* spp', considered to be more accurate (Gartner; 1977; Raffi and Flores, 1995). Previous studies of this genus have also avoided specific nomenclature due to the uncertainties of classification (Matsuoka and Okada, 1990; Matsuoka and Fujioka, 1992).

Previous studies relating to Quaternary cores in high latitudes

Previous research on Late Quaternary core sequences from high latitudes has identified abundance variations in calcareous nannoplankton assemblages which can be used to provide paleoceanographic information. An overview of a number of studies are given below demonstrating paleoceanographic interpretations based on calcareous nannoplankton.

Northern Hemisphere

Late Pleistocene and Holocene cores from the Norwegian Sea show that coccoliths are rare in late glacial sediments with an increase at glacial terminations and a maximum recorded in early Holocene sediments (Baumann and Matthiessen, 1992). Changes in dominance of species (*C. pelagicus* indicating cold water and *E. huxleyi* tolerating changes in temperature and salinity) shows the Norwegian Current with its present bio-chemical properties was established by 6 ka. Maxima of coccoliths between 9 ka to 8 ka, and 6 ka to 4 ka are associated with increased temperatures. The peak of reworked coccoliths recorded between 12 ka and 15 ka is interpreted as a massive reworking from the shelf into the deep sea during a transgression, or, the result of melting ice-rafted sediments.

Similarly, from the same region abundant coccoliths in stages 1, 5a, 5c and 5d indicate the presence of the warm North Atlantic water; the absence of coccoliths in stages 2 and 4 indicate polar conditions and the absence of the warm North Atlantic water. Variations in the abundance of small coccoliths in stage 3 indicates occasional periods of open water (Gard and Backman, 1990). Stage 5a showed the highest abundances of coccoliths with low abundances in stage 5e (the warmest SST in the past 500 ka). The low abundance of coccoliths in stage 5e is attributed to the presence of sea-ice in the North Atlantic during the warming interval which would suppress production of coccoliths. In the Arctic Ocean coccoliths are rare

with peaks in abundance recorded in stage 5a only, when warm North Atlantic water reached the Arctic Ocean.

An earlier study of Quaternary cores in the North Atlantic showed similar results (Gard, 1989a). Coccoliths in cores beneath polar waters are abundant during interglacial stages 1 and 5 with stages 3, 4, 6 and 7 virtually barren. The presence of *C. leptoporus* in some intervals of the most poleward cores may reflect past incursions of warmer waters into this region. Cores from the transitional region showed coccoliths in all stages with peaks of small coccoliths in stage 5e.

Differences were identified between cores from the Norwegian Sea and Greenland Sea spanning the past 12 ka (Samtleben et al., 1995b). Cores underlying relatively warm waters of the Norwegian Sea showed a peak in abundance between 10 ka and 8 ka, with a minimum for 8 ka to 5 ka, followed by a second maximum. In comparison, cores from the Greenland Sea underlying arctic waters contained few coccoliths. Changes in species composition through the Holocene identify four intervals related to different hydrographic regimes.

In the Arctic Ocean Quaternary sequences showed low abundance and diversity of coccoliths, where coccoliths are present only during interglacial intervals in cores from the most poleward locations, and peaks occur only in stages 1 and 5 in the most equatorward cores (Nowaczyk and Baumann, 1992). Differences between polar and equatorial locations show that sedimentation of coccoliths in interglacial periods occurred later in the high latitudes compared to lower latitudes. The termination of sedimentation of coccoliths at the end of the interglacial, approximately 65 ka, was consistent at all locations.

In the Labrador Sea abundance and diversity in two Quaternary cores (spanning oxygen isotopes stages 1 to 8) are interpreted as barren intervals indicating permanent ice cover; scarce nannofossils indicating low production, cold water and possibly seasonal ice cover; and, abundant

nannofossils indicating relatively warm conditions with no ice cover (Rhaman and de Vernal, 1994). The variation between warm-water and cold-water species is interpreted as indicating the presence of different water masses. Difference between the two core locations show the influence of warm North Atlantic surface water in the south during interglacial intervals but not the north, which probably remained under constant ice-cover for this period. The Polar Front is considered to have been as far south as 50°N in stage 2, preventing the North Atlantic Current from entering the Labrador Sea, retreating north at approximately 13 ka. The absence of warm-water species prior to 8.4 ka at 58°N, is interpreted as the presence of colder water currents and/or meltwater, resulting in a thin layer of low saline surface water, keeping the temperature of the photic zone cold and inhibiting nannoplankton production. The poleward-flowing Irminger Current was established by 8.4 ka, resulting in the increase of warm species at 58°N for this interval. The increase in *C. pelagicus* at 50°N lags behind the 58°N location interpreted as a cold water signal, with the equatorward-flowing Labrador Current not established until 9 ka.

Variation in morphology of *C. pelagicus* in Late Quaternary cores from the Norwegian-Greenland Sea is explained by changes in temperature related to the presence and absence of the warm North Atlantic water (Baumann 1995). Decrease in size was recorded for the Holocene and stage 7, interpreted as the absence of the warm North Atlantic water in high latitudes for these intervals. The presence of *Syracosphaera* spp., less resistant to dissolution, with high and low abundances of *C. pelagicus*, indicates dissolution has not concentrated *C. pelagicus* and the patterns observed are primary variations.

Southern Hemisphere

In the southwest Indian Ocean changes in coccolith assemblages were used to assess changes in the Agulhas Current during glacial-interglacial intervals of the Quaternary (Winter and Martin, 1990). The retroflexion of this current is associated with the position of the STF, where the

northward movement of the STF during glacial periods restricted the Agulhas Current to the Indian Ocean (Winter and Martin, 1990). The results showed no overall change in assemblage, indicating the position of the Agulhas Current was constant during the Late Quaternary. Five species comprised 90% of the sediments (*E. huxleyi, G. oceanica, G. ericsonii, C. leptoporus* and *U. sibogae*) indicating a continuous subtropical assemblage. Fluctuations in the abundance of *G. oceanica* are interpreted as paleoproductivity and eddy formation on the current boundary.

Quaternary cores from the subantarctic Pacific showed high percentages of *C. leptoporus* correlated with high percentages of warm-water radiolarian assemblages (Geitzenauer, 1969). Similarly, Pleistocene cores from the same region showed a correlation between peaks of warm-water calcareous nannoplankton (identified as *C. leptoporus* and *C. pelagicus*) and warm-water radiolaria and foraminifera species (Geitzenauer, 1972). Seven coccolith stages were identified, interpreted as fluctuations between glacial (dominated by *G. caribbeanica*) and cool interglacial (*C. leptoporus, C. pelagicus* and *G. caribbeanica*) intervals.

In the south Tasman Sea a general increase in productivity of surface waters during glacial intervals, compared to interglacial intervals, has been identified based on the $\delta^{18}O$ signal of calcareous nannoplankton in marine sediments for the past 500 ka (Dudley and Nelson, 1988). The $\delta^{18}O$ signal for calcareous nannoplankton is generally in phase with the $\delta^{18}O$ signal for foraminifera (Dudley and Nelson, 1989).

Oxygen isotope stages 1 to 12 are recognised based on calcareous nannoplankton assemblages from Quaternary sediments adjacent to Tasmania (Hiramatsu and De Deckker, 1997b). *F. profunda* is identified in all sediment samples in small percentages with increases during stages 5 and 7 coinciding with peaks of small *Gephyrocapsa* spp and small placoliths. The STF was poleward of the site for these intervals, according to these estimates. During interglacial intervals *C. leptoporus* increased

in abundance and *C. pelagicus* decreased, interpreted as high productivity during interglacials.

South of Australia (38°S) a Quaternary sequence of nannofossils and foraminifera indicates the absence of the warm-water Leeuwin Current and the movement of the STF equatorward of its present-day position during the glacial intervals of stages 10 and 12, (Wells and Okada, 1996). Unusually low winter SST and low abundance of *F. profunda* during the last 14 ka is interpreted as indicating persistent upwelling in this region for this interval. Stratigraphy based on calcareous nannoplankton showed the base of the core as stage 12, with two major hiatuses, the first between stage 2 and 10 and the second between stages 10 and 12.

Off the southwest coast of Australia stages 1 to 8 are identified from a Quaternary core sequence (Okada and Wells, 1997). Calcareous nannoplankton showed a successional change from *E. huxleyi* domination in stages 1 to 4, to small *Reticulofenestra* spp in the upper part of stage 5, small *Gephyrocapsa* spp in lower stage 5 through to stage 7, and *G. caribbeanica* at the base of the core. *F. profunda* was present in low numbers, attributed to low temperatures at this location throughout the Quaternary. No strong paleoenvironmental signals were recorded in the subordinate taxa, though, *C. leptoporus* showed a small increase in glacial stages 2 and 6.

Previous studies have documented the movement of oceanic fronts in the Southern Hemisphere based on faunal migrations (Howard and Prell, 1992; Morley, 1989), e.g., radiolarian assemblages spanning the Late Pleistocene and Holocene in the high latitudes of the South Indian Ocean. According to these studies, the STF and the PF migrated by up to 4° latitude poleward, and up to 7° latitude equatorward, with a maximum equatorward migration in stages 3, 5, and 12 (Morley, 1989; Howard and Prell, 1992). Based on these estimates the radiolarian fauna at the PF responded earlier than the fauna at the STF to global ice volume and global warming events (terminations).

Comparison of cores between the North and South Hemispheres

The study of Quaternary cores from the North and South Hemispheres noted a number of differences including *C. pelagicus* dominant in stage 1 in the Northern Hemisphere and stage 3 in the Southern Hemisphere; *C. leptoporus* never abundant in the Northern Hemisphere, with greatest numbers in stages 3 and 5e; *C. pelagicus* abundant in all samples, peaking in stage 5 in the Southern Hemisphere; and, *H. carteri* following the same trend as *C. leptoporus* (Gard, 1989b). Barren zones in the most poleward core of the Northern Hemisphere indicate full polar conditions, compared to the barren zone in stage 2 from the South Atlantic, interpreted as a dissolution rather than the northward movement of the PF.

A similar study noted that fluctuations of overall abundances of nannofossils were similar between the North and South Hemispheres with two exceptions. High overall abundances were found at approximately 650 ka in the subantarctic compared to a continuous low abundance in the subarctic from 500-1,000 ka; and, *C. pelagicus* occurs mainly in the Northern Hemisphere with higher abundances of *C. leptoporus* in the Southern Hemisphere (Gard and Crux, 1991). In the Norwegian Sea peaks of nannofossils are interpreted as an influx of warmer water from the south, and barren intervals are interpreted as a southward movement of the Polar Front. In the South Atlantic, the barren intervals for stages 2 and 6 coincide with the equatorward movement of the PF; stage 7 is dominated by small *Gephyrocapsa* spp with an increase in *C. leptoporus*, interpreted as milder conditions; and, the PF is interpreted as migrating equatorward during stages 10 and 11. The high abundances of *C. leptoporus* in stage 5e indicate the only interval warmer than present in the South Atlantic.

Chapter Three Techniques

A. **Water column samples**

B. **Sediment samples**

1. Light microscope samples
2. Scanning electron microscope samples
3. Sediment sample counting procedures

A. Water column samples

Water samples were collected during two cruises between Australia and Antarctica over two consecutive austral summers, 5th January to 27th January, 1994 and 28th January to 19th February 1995, between the latitudes of 41°S and 63°S. During the 1994 cruise, temperature, salinity and nutrient data were collected simultaneously (Rintoul et al., 1997) through the employment of a General Oceanics Mark IIIC CTD unit together with a model 1401 deck unit. Filter samples were collected with 10-litre General Oceanics Niskin bottles on a 24-bottle Model 1015 rosette pylon. Samples, a total of 46, for this study were collected from 10 stations, between water depths of 13m to 184m. Between one and two litres of water were filtered for each sample.

During the second transect (1995) water samples were collected using 12-litre General Oceanics Niskin bottles, Model 1010. The bottles were employed on a single cable and triggered consecutively when the cable and the bottles were in position. Six stations were sampled between 12m and 240m for a total of 34 filtered samples. Between 2 and 8.1 litres of water were filtered for each sample. A submersible SDL logger was used in conjunction with the Niskin bottles to profile the temperature and salinity of the upper 200m of the water column. Nutrient (phosphate, nitrate and silicate) levels were measured for each sample.

Water samples from both cruises were filtered through 47mm diameter Millepore filters with a pore size of 0.8µm, using a vacuum pump. The filters were air dried at room temperature in a non-contaminated cabinet and when dry, stored in covered plastic petri dishes.

All samples were examined with the use of scanning electron microscopes, JEOL JSM-840 and Phillips 505. Samples were prepared by placing a small piece of filter (approximately $5mm^2$) onto double-sided carbon tape which was mounted on a stub, and coated with gold. All samples were counted at the same magnification (x2500). This piece of filter was sampled away from the border of the whole filter to ensure a uniform distribution, although, the study by Knappertsbusch and Brummer (1995) showed no relationship between the location on the filter and particle density.

With a 300 to 350 count (of coccospheres) there is a 95% chance of finding species at the 0.1% level (McIntyre and Bé, 1967). However, low numbers of coccospheres in the austral summer 1994 data set (south of the Subtropical Front) proved a count of 300 to be impractical, e.g., a filter area of $1.6527mm^2$ recorded only 20 coccospheres (Appendix B1).

Alternatively, a set area of filter (minimum of 400 SEM screens) was counted for each sample. An initial survey was carried out on nine samples collected from eight stations at various depths (Fig. 17) to determine the number of screens necessary to give a true representation of abundance and diversity. This follows, in part, the rarefaction method outlined by Sanders (1968). Sanders' (1968) approach is a diversity measurement independent of sample size and is dependent upon the shape of the species abundance curve, not the absolute numbers of specimens per sample (as the number of individuals increases the number of species decreases at a logarithmic rate resulting in a curvilinear line). The species abundance curves are found to reach a point where they plateau, i.e., where numbers of all species, including rare species, remain constant regardless of a continuing increase of individuals.

For this study three different morphotypes of *E. huxleyi* were selected to represent the 'species', Type X, the 'cold water' form (Plate 1; Fig. 2); Type Y, the 'polar' form (Plate 1; Fig. 3); and, Type Z, a severely dissolved form (Plate 1; Fig. 4). The results show 400 screens to be the approximate point where the percentages of the different morphotypes of *E. huxleyi* remain constant regardless of the number of individuals counted (Fig. 17). The data for this experiment was taken from a separate count of these morphotypes which was carried out to determine changes in abundance (of morphotypes) with relation to depth and latitude, as discussed in Chapter Four (Appendix B3; Fig. 27)

In water column samples only whole coccospheres were counted. The coccolithophore standing crop, or cell density, is determined by calculating the number of coccospheres per litre (Appendices B1, B2). An example of these calculations follows, based on 37 coccospheres counted for 400 screens from one filter, with 1.5 litres of water filtered.

* The diameter of filter exposed to filtrate:	=	40mm
1 SEM screen with a magnification of x2500	=	36x46µm
	=	$(0.036x0.046)mm^2$
	=	$0.0016mm^2$
**400 SEM screens @ 0.001656 mm^2	=	0.66 mm^2
Total area of exposed filter	=	$3.14x(20mm)^2$
	=	3.14x400 mm^2
	=	1256 mm^2
Volume of filtrate for whole filter	=	1.5 ltr

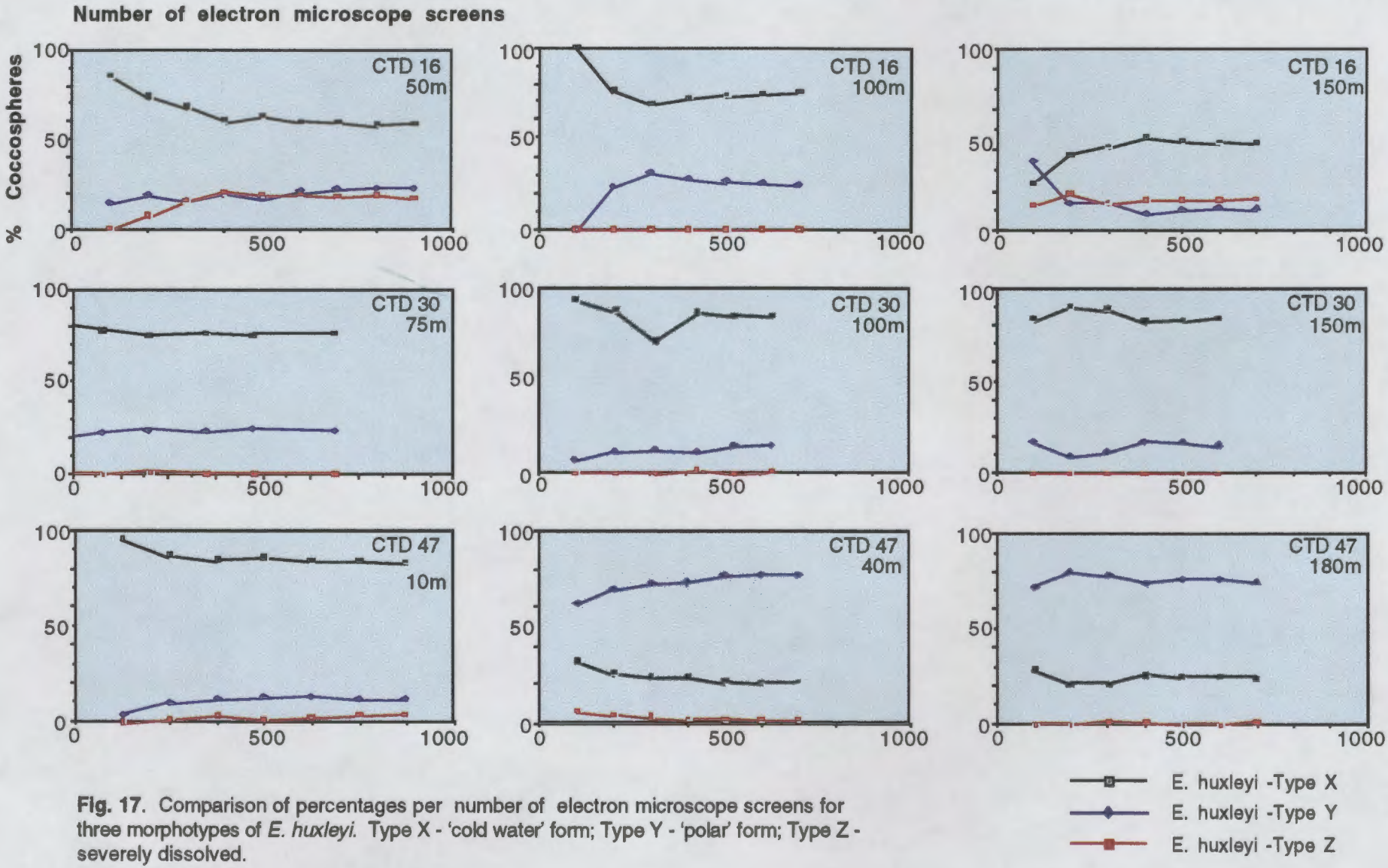


Fig. 17. Comparison of percentages per number of electron microscope screens for three morphotypes of *E. huxleyi*. Type X - 'cold water' form; Type Y - 'polar' form; Type Z - severely dissolved.

Volume of filtrate for 400 screens = $1.5/1256mm^2 x 0.66mm^2$

= 0.0012x0.66

= 0.00079 ltr

Coccospheres per litre

37 coccospheres per 400 screens = 37/0.00079 ltr

= 46,835 per litre

* The diameter for each filter was 47mm with the diameter of 40mm exposed to the filtrate.

** Total area of filter counted per sample/filter. Each screen was viewed precisely without overlapping each other as there were distinctive features on each screen to allow for precise movement.

Data from these results are referred to in terms of relative abundance for individual species reflecting a semi-quantitative analysis. Statistical analysis of this data is recognised as limited due to the counting method employed, i.e., number of coccospheres per 400 screens. An alternative method of counting coccospheres per individual screen for 400 screens and finding the mean and standard deviation per screen from the 400 screens, would allow for more precise quantitative analysis.

B. Sediment Samples

Sediment samples were collected from three different sources. Two collections were made during research cruises in the Southern Ocean using box, gravity and piston cores (Table 1). The remaining sediments were collected as dried material from the archives of the Department of Geology and Oceanography at the University of Bordeaux.

Surface sediment and downcore samples collected during research cruises were taken immediately after the cores arrived on board and placed in plastic vials. The surface sediment samples were taken from the top 1cm

of cores and downcore sediment samples were sampled at regular intervals. These samples were then oven dried at 60°C in the collection vials.

Light microscope samples

Smear slides of dry sediment samples were prepared for the light microscope by mixing a small quantity of dry sediment to a thin paste using distilled water, buffered with NaOH to ensure a pH of 7. The resulting paste was spread very thinly across the slide with the use of a clean, flat wooden toothpick. The glass slide was placed on a hotplate to ensure fast drying before the sediment slurry had time to coagulate. When dry, the glass slide was lightly scraped once with a sterile razor blade to remove excess thickness of sediment. A cover slip was then mounted using a small amount of the ultraviolet light sensitive LV potting compound, *Loctite Impruv*$_{TM}$. Slides were then place under an ultraviolet light until set (approximately 15 to 20 minutes).

Initially preparations involved the light crushing of sediments using a small pestle and mortar to break up aggregates before spreading onto the glass slide. A number of samples from core GC07 were prepared with both methods (i.e., with and without the pestle and mortar) and examined under a light microscope. The two methods showed similar results (Appendix A1 - LM count 1 using pestle and mortal; LM count 2 without pestle and mortar) suggesting that mixing directly onto the glass slide is sufficient to disaggregate the sediments from this region. The samples contained few clay particles and ultrasonification, addition of anti-flocculants and centrifuging was found to be unnecessary. Similarly, Geitzenauer (1972) found sediments from the same region abundant in coccoliths and counting for those samples were made directly from a suspension of raw sediments with no prior preparation.

The examination of prepared glass slides was carried out using a Zeiss Axioskop light microscope with an oil immersion objective of x100

Sample	Type of core	Water depth (m)	Date Collected	Latitude	Longitude	Recovered (m)
MD 88 777	gravity	3250	24/1/88	49°14.90S	137°32.82E	16.05
MD 88 778	gravity	3540	25/1/88	46°57.79S	145°15.37E	7.8
KR 8807	gravity	2890	28/1/88	47°08.87S	145°47.80E	0.3
MD 88 779	gravity	2260	29/1/88	47°50.69S	146°32.75E	6.7
KR 8808	gravity	3885	30/1/88	49°15.69S	148°48.15E	
MD 88 780	gravity	3890	30/1/88	49°16.44S	148°49.21E	5.4
MD 88 781	gravity	2490	31/1/88	49°07.52S	149°35.91E	4.3
KR 8809	gravity	4350	31/1/88	50°35.60S	147°09.32E	1
MD 88 782	gravity	4350	2/1/88	50°35.52S	147°08.69E	1
MD 88 783	gravity	3170	2/1/88	52°23.57S	144°49.11E	3
KR 8810	gravity	2785	2/2/88	54°11.16S	144°47.95E	0.9
MD 88 784	gravity	2800	2/2/88	54°11.48S	144°47.65E	5
KR 8811	gravity	2880	2/2/88	54°55.07S	144°04.04E	0.7
MD 88 786	gravity	2910	2/2/88	54°55.86S	144°05.15E	3
MD 88 787	gravity	3020	2/3/88	56°22.72S	145°17.56E	10.4
MD 88 788	gravity	3742	2/4/88	57°56.57S	144°35.58E	9.5
KR 8813	gravity	3740	2/4/88	57°56.86S	144°35.03E	0.6
GC01	gravity	4238	30/1/95	44°10.30S	144°10.86E	3.78
GC04	gravity	2981	31/1/95	44°05.99S	144°15.00E	2.57
GC05	gravity	2334	1/2/95	44°03.99S	145°10.86E	1.8
GC06	gravity	2609	2/2/95	44°31.51S	146°42.48E	0.86
GC07	gravity	2334	2/2/95	45°09.52S	146°17.51E	5.3
GC11	gravity	2406	6/2/95	45°44.02S	144°53.05E	2.64
GC13	gravity	4452	7/2/95	46°10.01S	144°16.00E	5.3
GC14	gravity	3360	7/2/95	46°26.98S	145°14.47E	6.29
GC16	gravity	3523	8/2/95	46°47.99S	145°14.99E	3.58
GC17	gravity	3001	10/2/95	47°45.04S	145°49.00E	2.29
GC20	gravity	3300	11/2/95	48°39.03S	146°26.02E	3.53
GC21	gravity	4132	12/2/95	49°00.05S	145°59.01E	3.71
GR001	gravity	1311	13/2/95	47°39.60S	147°32.98E	0.08
GC28	gravity	3065	16/2/95	46°03.48S	147°23.01E	2.68
GC30	gravity	2968	16/2/95	46°09.99S	147°27.97E	5.19
GC31	gravity	3440	18/2/95	44°32.79S	149°03.80E	5.23
GC32	gravity	2650	18/2/95	43°57.93S	149°55.18E	2.64
GC34	gravity	4202	23/2/95	45°06.00S	147°44.50E	5.16
GC35	gravity	2720	24/2/95	45°44.00S	146°32.00E	2.05
MD 97 2106	gravity	3310	7/5/97	45°09.69S	146°16.51E	2.34
MD 97 2107	piston (calypso)	2950	8/5/97	47°42.70S	145°46.59E	4.14
MD 97 2108	box	2140	9/5/97	48°29.28S	149°06.33E	0.21
MD 97 2110	gravity	1345	13/5/97	48°25.74S	176°34.31E	2.8
MD 97 2112	piston (calypso)	3975	16/5/97	41°15.70S	171°19.64W	24.39
MD 97 2113	piston (calypso)	2936	16/5/97	42°00.80S	171°19.26W	24.19
MD 97 2115	piston (calypso)	2160	16/5/97	43°10.84S	171°48.55W	34.6
MD 97 2118	piston (calypso)	2690	19/5/97	45°07.01S	179°10.80W	25.46

Table 1.
Core and surface sediment samples;
type of core, water depth, date collected latitude, longitude and amount recovered.

magnification and eyepiece of x10 magnification, resulting in a total of x1000 magnification.

Scanning Electron Microscope Samples

Samples for the SEM were prepared using the same technique, substituting mica slides for glass slides and placed inside individual plastic bags for storage. Small areas from the mica slides (approximately 7mm^2) were mounted on SEM stubs and coated with gold. Initial counting was carried out with the use of a JEOL SEM and a Phillips SEM at x2500 magnification. Photography of samples was taken at various magnifications.

A minimum of 300 coccoliths were counted for the sediment samples (Appendix A1, A2, A3 and A4), following the principle outlined by McIntyre and Bé (1967, and references therein). Counting followed a systematic direction of transects across the light microscope slides and the SEM stubs to ensure that no area was counted twice.

Sediment Sample Counting Procedures

For the purposes of this sediment study only whole individual coccoliths were counted (i.e., not fragments) without reference to whole coccospheres. Previous studies (Samtleben and Schröder, 1992; Knappertsbusch, 1993) have included a semi-quantitative measurement of whole coccospheres preserved in sediments by allocating a set amount of coccoliths per individual species, for example *E. huxleyi* is considered to have 23 coccoliths per coccosphere, *C. leptoporus* 31 coccoliths, *H. carteri* 24 coccoliths etc. This was done in order to correlate the standing crop in the surface waters with that of the surface sediments and to provide a measure of the carbonate flux through the water column. As the number of coccoliths vary in size and number between individual coccospheres within some species (Plate 2; Fig. 1) and some coccospheres may have multiple layers of coccoliths (Plate 1; Fig. 7), these

measurements were not considered reliable and were not adopted in this study.

The first count for all samples in core GC07 (Appendix A1) and all surface sediment samples (Appendix A2) were counted for the categories *E. huxleyi*, individual *Gephyrocapsa* spp and the single category 'subordinate spp' which includes all other species. This count, of 300 coccoliths or more using a light microscope, identified those samples dominated by *E. huxleyi* , i.e., with an age younger than 73 ka based on the biostratigraphic scheme of Thierstein et al. (1977). The resulting percentages reflect percentages of the total assemblage. A number of the same samples were re-counted using a scanning electron microscope and showed some variation. Repeated counts using the light microscope were consistent and it is considered the light microscope counts were the most accurate and were used where possible, depending on availability of equipment.

A second count of 300 coccoliths or more was made for all subordinate species for GC07 (Appendix A1) and surface sediments (Appendix A3) excluding *E. huxleyi* and *Gephyrocapsa* spp; these percentages reflect those within the subordinate group only. This step-wise counting method follows that outlined by Biekart, (1989 and references therein) and is used in assemblages which are dominated by one or two species to overcome the bias of this dominance.

A separate count was made for a number of cores, GC04, GC20, GC31, GC32, GC34 and GC35, and for these cores, one count only was made for all species, i.e., the percentages are relative abundances of the total assemblage (Appendix A3).

Chapter Four Water Column Data

A. **Introduction**

1. Regional oceanography

B. **Results**

1. Standing crop
2. Temperature
3. Salinity
4. Nutrients
5. Species
6. Floral assemblages

C. **Discussion**

1. Standing crop
2. Temperature
3. Salinity
4. Nutrients
5. Species
6. Floral assemblages

D. **Summary**

1. Standing crop
2. Species
3. Floral assemblages

A. Introduction

The aim of this section of the study is to establish the density and diversity of coccolithophore populations within the surface and subsurface water (upper 200m) of the Australian Sector of the Southern Ocean. These data were compared to a series of physico-chemical factors (temperature, salinity and nutrients) to assess the control of water masses

and associated hydrological fronts on the distributional pattern of extant coccolithophores.

Station No. (Date)	Latitude (°S)	Longitude (°E)	Water depth (m)	Coccospheres per litre	T°C	Salinity (‰)	NO_3 (µmol/l)	PO_4 (µmol/l)	SiO_3 (µmol/l)
CTD 16	48°18.8'	144°32.1'	14	174789	9.44	34.31	12.70	0.94	1.10
(5/1/94)			28	264991	9.43	34.31	12.80	0.95	1.50
			53	168842	9.11	34.33	13.80	1.07	2.20
			103	34907	8.53	34.47	15.90	1.16	4.50
			152	59442	8.6	34.53	15.60	1.14	4.50
CTD 21	49°45.0'	143°52.1'	14	373728	9.66	34.43	11.80	0.87	2.10
(5/1/94)			29	496694	9.63	34.44	11.80	0.88	1.50
			53	286462	9.54	34.44	12.00	0.93	1.40
			103	46795	9.1	34.49	13.80	1.06	3.50
			156	25295	8.77	34.55	15.20	1.09	3.90
SUBANTARCTIC FRONT									
CTD 30	52°38.3'	142°23.2'	13	165047	5.49	33.85	23.20	*	1.50
(8/1/94)			53	197298	5.41	33.85	23.20	1.56	1.40
			77	178643	4.72	33.85	23.50	1.63	1.20
			103	82004	2.9	33.89	25.60	1.95	8.10
			154	58178	2.11	33.94	27.70	2.01	13.90
POLAR FRONT									
CTD 37	55°01.1'	141°00.5'	14	163150	4.11	33.89	25.60	*	5.30
(9/1/94)			53	92325	2.33	33.88	26.20	1.82	5.30
			103	49325	1.41	33.92	27.20	2.03	14.90
			152	47427	0.47	33.94	29.20	2.12	24.40
CTD 39	55°55.7'	140°24.4'	13	195401	4.03	33.89	25.30	*	3.20
(10/1/94)			62	166945	2.41	33.89	26.20	1.84	7.30
			102	71567	1.95	33.91	26.90	1.95	12.30
CTD 43	57°23.0'	139°50.8'	13	138488	4.28	33.9	25.30	*	4.40
(10/1/94)			42	28456	2.63	33.89	25.00	1.69	1.90
			127	81812	1.34	33.93	28.10	2.06	17.00
CTD 47	58°51.2'	139°50.5'	14	199195	3.52	33.9	26.10	*	8.50
(11/1/94)			45	244726	2.1	33.91	25.50	1.72	2.70
			130	28456	0.29	33.95	28.90	2.12	24.70
			184	258954	0.38	34.04	30.90	2.19	33.20
CTD 51	60°21.3'	139°50.5'	13	13280	2.02	33.94	27.60	*	22.70
(12/1/94)			55	9485	0.61	33.95	27.40	1.73	18.50
			103	7588	-0.22	33.96	29.00	2.04	31.10
			145	0	0.47	34.21	33.70	2.36	50.90
CTD 54	61°20.9'	139°50.9'	13	15330	1.93	33.94	27.90	*	23.00
(13/1/94)			54	28456	0.47	33.96	28.00	1.81	21.80
			103	8300	-0.3	33.97	29.60	2.10	34.60
			135	2098	-0.23	34.09	32.00	2.26	44.40
ANTARCTIC DIVERGENCE									
CTD 59	63°21.1'	139°50.7'	14	0	0.83	33.75	29.00	*	54.90
(14/1/94)			56	0	-1.07	34.18	31.10	2.19	58.20
			103	#	1.54	34.53	35.20	2.48	72.70
			153	0	1.86	34.6	34.90	2.46	76.70

Table 2 Number of coccospheres per litre of water, salinity, temperature and nutrient values for CTD stations, austral summer 1994.

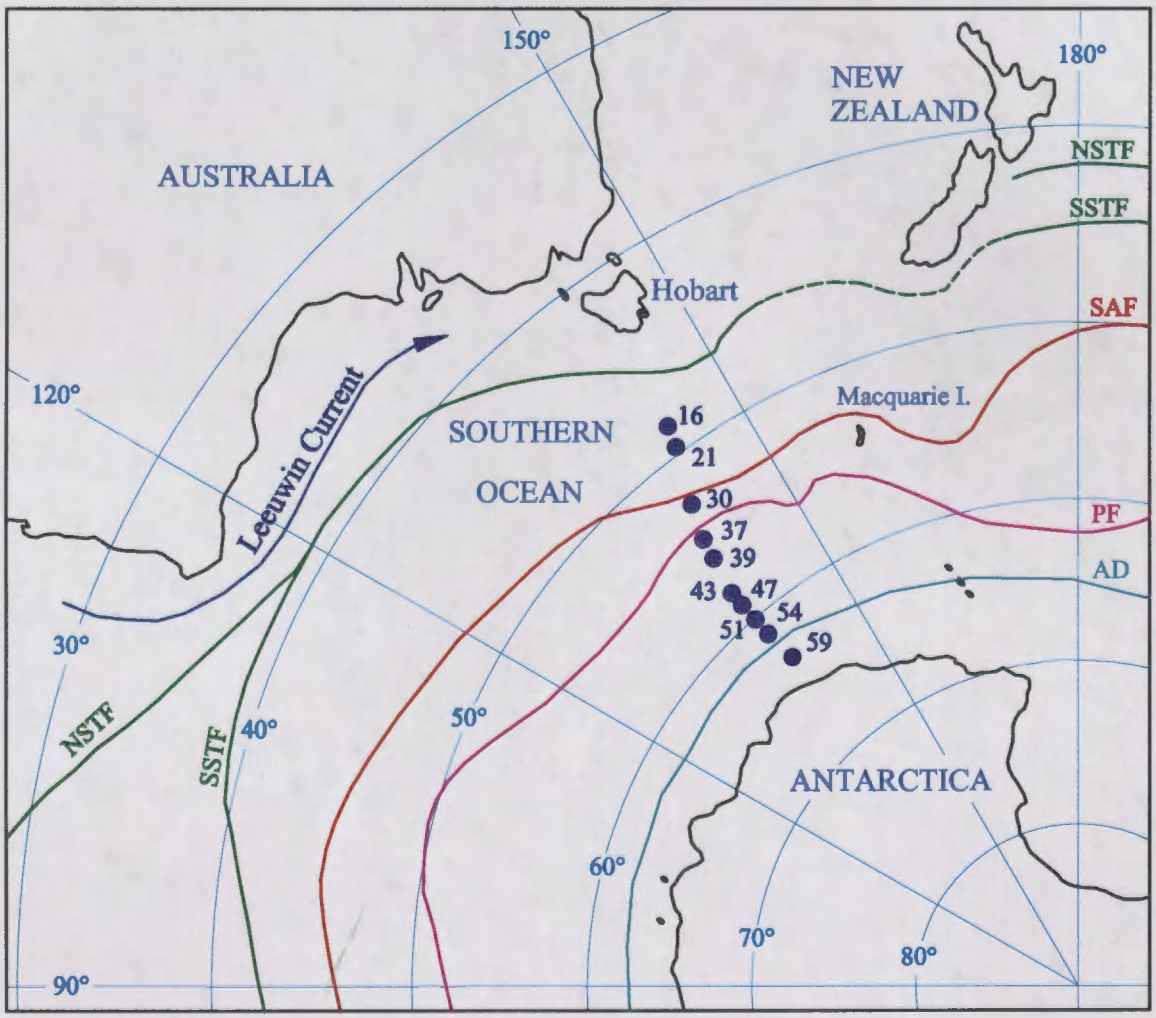


Fig. 18 Location of water samples (CTD) collected during austral summer 1994.

Samples were collected during two transects. The first transect, during austral summer 1994, collected temperature, salinity and nutrient data (Rintoul et al., 1997) in conjunction with filter samples. Ten stations were sampled between 48°S and 61°S with a total of 41 samples collected (Fig. 18). This cruise was part of the World Ocean Circulation Experiment (WOCE) section SR3 (Table 2).

Station No. (Date)	Latitude (°S)	Longitude (°E)	Water depth (m)	Coccospheres per litre	T (°C)	Salinity (‰)	NO_3 (µmol/l)	PO_4 (µmol/l)	SiO_3 (µmol/l)
HC001	41°00.3'	142°31.0'	12	49957	15.70	35.37	0.044	0.293	1.213
(28/1/95)			56	208206	12.80	35.17	3.078	0.491	0.686
			110	13284	11.20	35.26	8.554	0.822	2.127
			164	11383	10.60	35.23	*	*	*
			218	47111	10.30	35.23	10.73	0.886	3.275
HC002	43°00.0'	143°02.0'	14	80943	15.21	35.34	1.21	0.377	1
(29/1/95)			28	49957	13.87	35.39	*	0.263	0.895
			55	66715	13.25	35.51	4.444	0.564	1.318
			110	27508	11.64	35.41	9.144	0.828	2.239
			163	43633	10.92	35.31	*	*	*
			219	#	10.55	35.31	11.753	0.97	3.527
HC004	45°02.0'	144°15.1'	17	138488	14.23	35.38	1.644	0.368	1.049
(5/2/95)			34	108135	14.26	35.39	1.559	0.38	0.924
			62	160621	13.36	35.36	3.524	0.471	0.918
			120	40752	11.51	35.26	9.211	0.773	2.131
			180	6956	10.91	35.31	10.818	0.903	4.562
			240	6007	10.36	35.23	11.625	0.935	4.003
SUBTROPICAL FRONT									
HC005	47°11.9'	145°4.3'	19	86634	11.80	35.14	6.631	0.686	1.461
(9/2/95)			35	79678	11.80	35.14	6.577	0.655	1.34
			62	38574	11.78	35.14	6.527	0.679	1.212
			117	21817	10.55	35.11	10.847	0.973	1.994
			172	9756	10.48	35.21	*	*	*
			227	6324	9.67	35.15	13.662	1.08	3.922
HC007	49°04.5'	146°15.0'	19	117620	9.39	34.65	15.389	1.097	1.449
(12/2/95)			35	58178	9.34	34.65	15.261	1.097	1.586
			62	63553	9.02	34.69	15.575	1.133	2.044
			117	37468	8.35	34.8	15.745	1.23	5.005
			172	6166	8.81	35.06	14.418	1.119	4.938
			227	3035	8.45	35.03	15.518	1.16	5.376
HC009	43°54.4'	151°22.0'	14	27192	18.46	35.64	3.482	0.208	0.675
(19/2/95)			29	42368	18.45	35.66	3.657	0.211	0.752
			55	21500	16.47	35.56	3.939	0.259	1.021
			109	7209	13.78	35.55	8.159	0.717	2.845
			164	4174	12.97	35.53	9.102	0.778	3.596
			217	3415	12.50	35.53	8.764	0.722	2.804

Table 3 Number of coccospheres per litre of water, salinity, temperature and nutrient values for HC00 stations, austral summer 1995.

The second transect, during austral summer 1995, collected samples between 41°S to 49°S. Six stations were sampled with a total of 34 samples collected (Fig. 19). Temperature, salinity and nutrient data were recorded

for each sample. Five stations were sampled in a poleward direction to the west of Tasmania, with a sixth station (HC009) sampled to the east (Table 3).

Regional Oceanography

The major oceanographic fronts in the study area can be summarised as follows based on the definitions given by Rintoul et al. (1997) and Belkin and Gordon (1996, and references therein):

Subtropical Front	12°C isotherm at 150m
Subantarctic Front	largest horizontal gradient in the temperature range of 3-8°C at 300m depth
Polar Front	northern most extent of the 2°C isotherm in the temperature minimum layer
Antarctic Divergence	doming of the isotherms at approximately 63°S to 64°S

Based on these definitions and data collected during 1994, the STF with a surface expression of approximately 13°C, was located between 45°S and 46°S (Figs 20). Remote sensing images of sea surface temperature (SST) for January 1994 confirm this position (Fig. 21). The ten stations sampled for calcareous nannoplankton during 1994 are south of this front. During austral summer 1995 the STF was located between 45°S and 47°S, confirmed by remote sensing images of SST for January and February 1995 (Fig. 22), which clearly depicts the associated meanders and eddies.

The position of the SAF for austral summer 1994 is located between 50°S and 52°S with a surface expression of approximately 7°C to 9°C (Fig. 7)

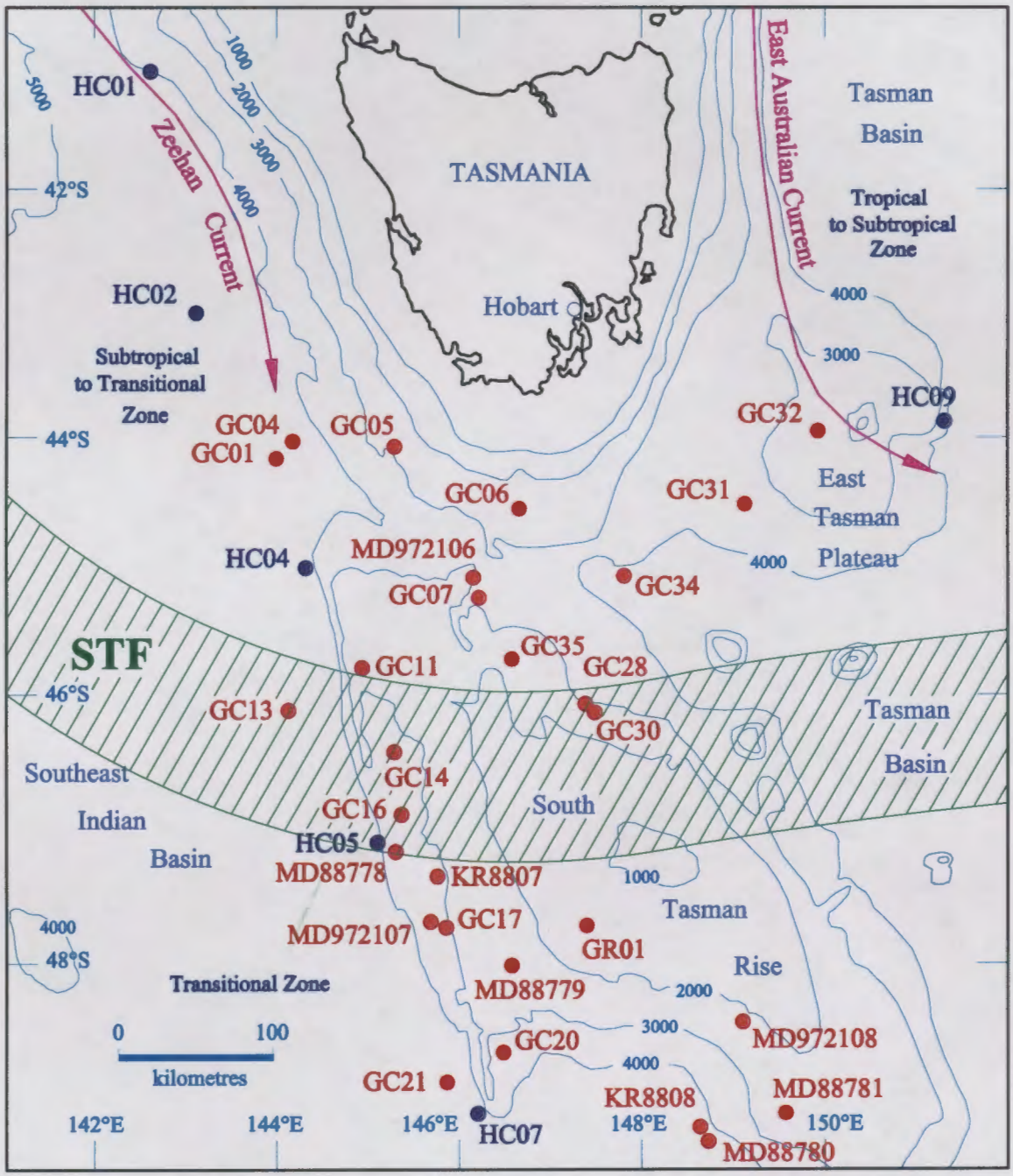
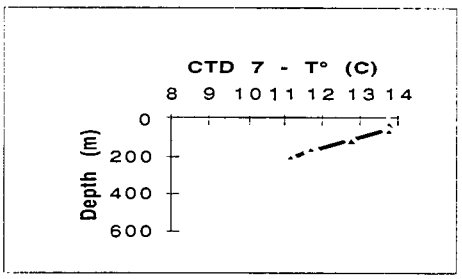
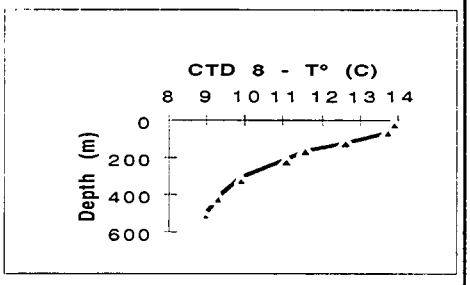


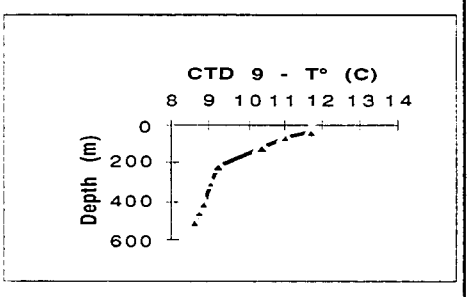
Fig. 19 Map of South Tasman Rise with locations of water samples for austral summer 1995, and sediment samples collected in 1988, 1995 and 1997.

confirmed by the remote sensing imagery (Fig. 21). Stations sampled in austral summer 1995 are located to the north of this front.

Station	Temperature (°C)	Water Depth (m)
CTD 7	13.72	14.26
45°12'S	13.72	14.48
145°51'E	13.73	27.99
	13.73	27.9
	13.72	53.41
	13.72	54.16
	12.74	103.73
	12.74	104.71
	11.74	152.62
	11.69	153.53
	11.11	203.86
	11.11	204.38
CTD 8	13.89	14.9
45°12'S	13.72	54.85
145°51'E	12.56	104.85
	11.55	153.84
	11.03	204.94
	9.88	306.69
	9.25	406.39
	8.91	505.46
SUBTROPICAL FRONT		
CTD 9	11.71	15.06
45°41'S	11.65	29.95
145°39'E	10.95	54.86
	10.36	106.25
	9.18	206.38
	9	307.19
	8.8	404.53
	8.7	455.61
	8.55	504.97
CTD 10	11.46	15.58
46°10'S	11.43	27.5
145°27'E	11.01	53.98
	10.24	104.81
	9.68	129.93
	9.41	154.98
	9.27	205.96
	8.96	304.5
	8.67	405.69







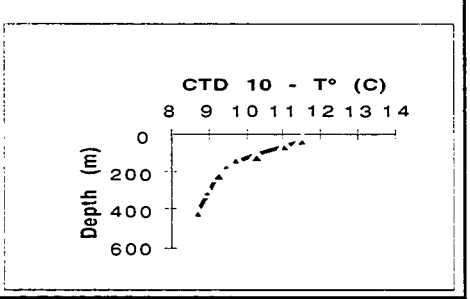


Fig. 20 Temperature profiles for CTD stations demonstrating the position of the Subtropical Front with a surface expression of 13°C for austral summer 1994.

The PF with a SST expression of approximately 5°C was located between 53°S and 55°S during austral summer 1994 (Fig. 7). The same front was identified at approximately 56°S for austral summer 1982-83 (Nishida,

1986). The position of this front is variable over 1° to 2° latitude (Gordon, 1971) due to mesoscale meanders and eddies, sometimes with a duration of only one week (Edwards and Emery, 1982). The remote sensing data for January 1994 confirms the position and variability of PF (Fig. 21).

The region of upwelling at the Antarctic Divergence (AD) is recognised by the doming of subsurface isotherms (Rintoul, pers. comm.) between 63°S and 64°S for austral summer 1994 (Fig. 7). The AD occurs at a surface temperature of 0.5°C to 1°C, and is not visible on the remote sensing imagery (Fig. 21) due to cloud cover at the time.

Only one station (CTD 30) is located between the SAF and PF, where these two fronts are in close proximity resulting from the poleward shift of the STF and SAF and the equatorward shift of the PF (Fig. 5).

B. Results

Standing Crop

Figures 23 and 25 show the cell densities of calcareous nannoplankton decrease with increased latitude. Figures 23, 24, 25 and 26 are generated from the data in Tables 2 and 3. All depths are represented at each station, although some depths (e.g., 28m at 41°S) may not have been sampled for particular stations, resulting in artefacts produced by the graphing package (Fig. 25; Coccospheres/ltr; 41°S). The decrease in cell densities is coupled with an overall decrease of temperature and salinity and an increase in nitrate and phosphate (Figs 23, 24, 25, 26). During austral summer 1994 (Appendix B1) highest abundance and diversity of coccolithophorids occurred north of the SAF. In 1995 highest abundances occurred north of the STF (Table 2) and highest diversities south of the STF (Appendix B2).

Lower cell densities were recorded in all samples for 1995 compared for 1994. In a vertical profile, highest cell density and diversity were recorded

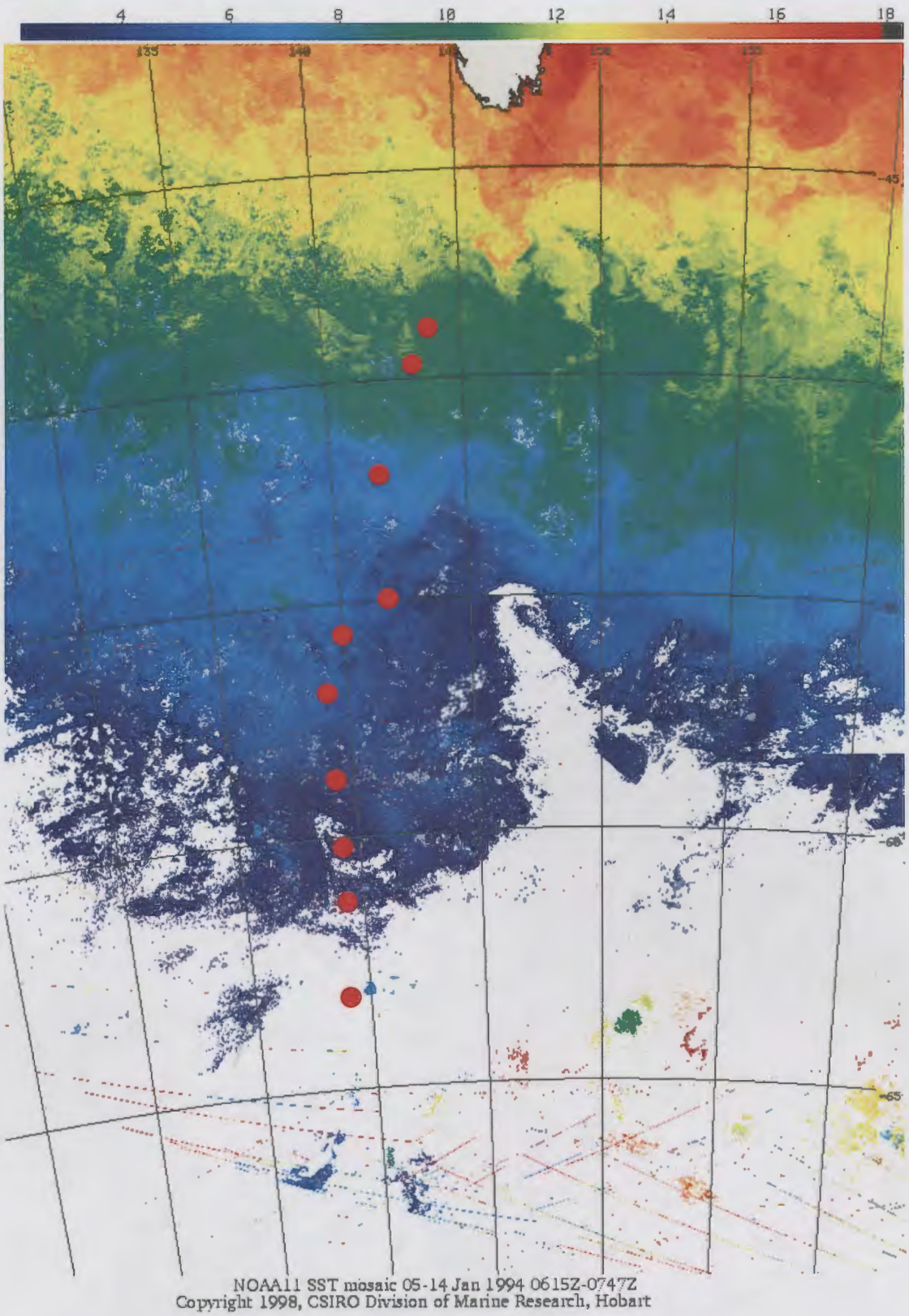


Fig. 21 Remote sensing image of sea surface temperatures between Australia and Antarctica for January 1994. The red circles represent locations of stations sampled during austral summer 1994. The Subtropical Front is defined by the 13 °C isotherm (boundary of yellow and orange); the Subantarctic Front by the 7 °C – 9 °C isotherms (boundary between blue and green); and the Polar Front by the 5 °C isotherm (boundary between light blue and dark blue).

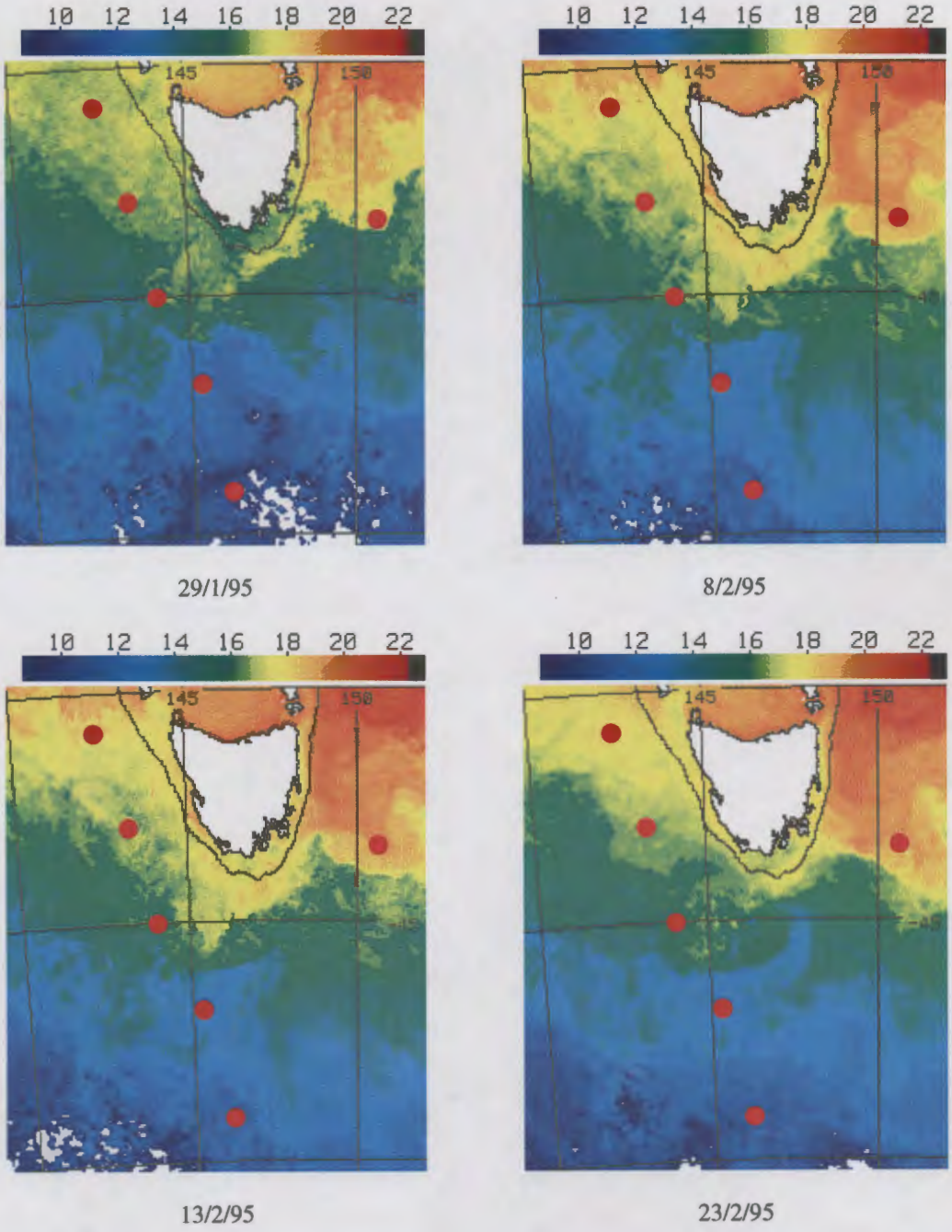


Fig. 22 Remote sensing images of sea surface temperatures south of Tasmania for January and February 1995. The red circles represent locations of stations sampled during austral summer 1995. The Subtropical Front is defined by the 13 °C isotherm (boundary between green and blue).

at approximately 50m water depth north of the STF (Fig. 25), and between 10m and 35m south of the STF (Fig. 23).

Across the SAF poleward decreases in temperature and salinity combined with increases in nitrate and phosphate were recorded in the upper 14m of the water corresponding with a reduction in productivity (Table 2; Figs 23, 24).

Between the SAF and the PF only two species were present, *E. huxleyi* and *C. leptoporus*. Between the PF and the AD, 18 of 22 samples contained a monospecific assemblage of *E. huxleyi*, three samples (between ~60°S and 62°S) contained semi-calcified polar species in conjunction with *E. huxleyi* and one sample was barren (at ~60°S; 145m). South of the Antarctic Divergence (~63°S) all four water samples were barren of calcareous nannoplankton (Table 2).

Temperature

Distinct changes in temperature were registered across each of the frontal zones and correspond to changes within the calcareous nannoplankton assemblages. Across the STF a decrease of approximately 2°C to 3°C was found in the upper 100m; across the SAF approximately 4°C; across the PF approximately 1°C in the surface waters and 3°C difference at 53m depth. A fourth temperature drop was recorded between station 59°S (CTD 47) and 61°S (CTD 51) of approximately 1.5°C.

The minimum temperatures recorded for coccospheres in the photic zone include, -0.2°C (CTD 51, 103m); 0.38°C (CTD 47, 184m); and, -0.23°C (CTD 54, 135m).

Salinity

Changes in surface salinity in a poleward direction across the frontal zones include a decrease of 0.24‰ across the STF, 0.58‰ across the SAF

and 0.19‰ across the AD. In contrast, the PF showed a small increase of 0.05‰. In a vertical profile salinity measurements are highest in the upper 50m to 60m north of the STF (Fig. 25) and below 100m south of this front (Fig. 23). The highest measurements were taken at HC009 (not included in Fig. 25), east of Tasmania (Table 3).

Nutrients

Nitrate and Phosphate

Nitrate and phosphate concentrations increased poleward in surface waters with highest readings at the most poleward stations. Increases in nitrate registered approximately 4.9 µmol/l across the STF; 11.4 µmol/l across the SAF; and, 2.4 µmol/l across the PF. Phosphate showed an increase of 0.39 µmol/l across the STF with no data available for the remaining frontal zones. In a vertical profile at each station, nitrate and phosphate levels increase at depth (Figs 24, 26) with a corresponding decrease in coccosphere abundances.

Silicate

Silicate concentrations show an increase poleward in surface waters, particularly south of 60°S and across the AD (Fig. 24), with increases of 0.4 µmol/l across the STF; 0.6 µmol/l across the SAF; 3.8 µmol/l across the PF; and, 31.9 µmol/l across the AD. At 60°S, between CTD 47 and CTD 51, an increase of 14.2 µmol/l was noted. In a vertical profile silicate increases at depth, particularly below 100m south of the PF (Fig. 24). In general, cell density decreases with increased silicate with some exceptions, e.g., CTD 30 (52°S) between 53m and 77m. This anomaly is attributed to the mixing of surface waters in this region.

Species

Temperature and environmental preferences for the more common species is comparable to previous findings (Table 4), with some minor differences including a lower minimum temperature for *E. huxleyi* and a

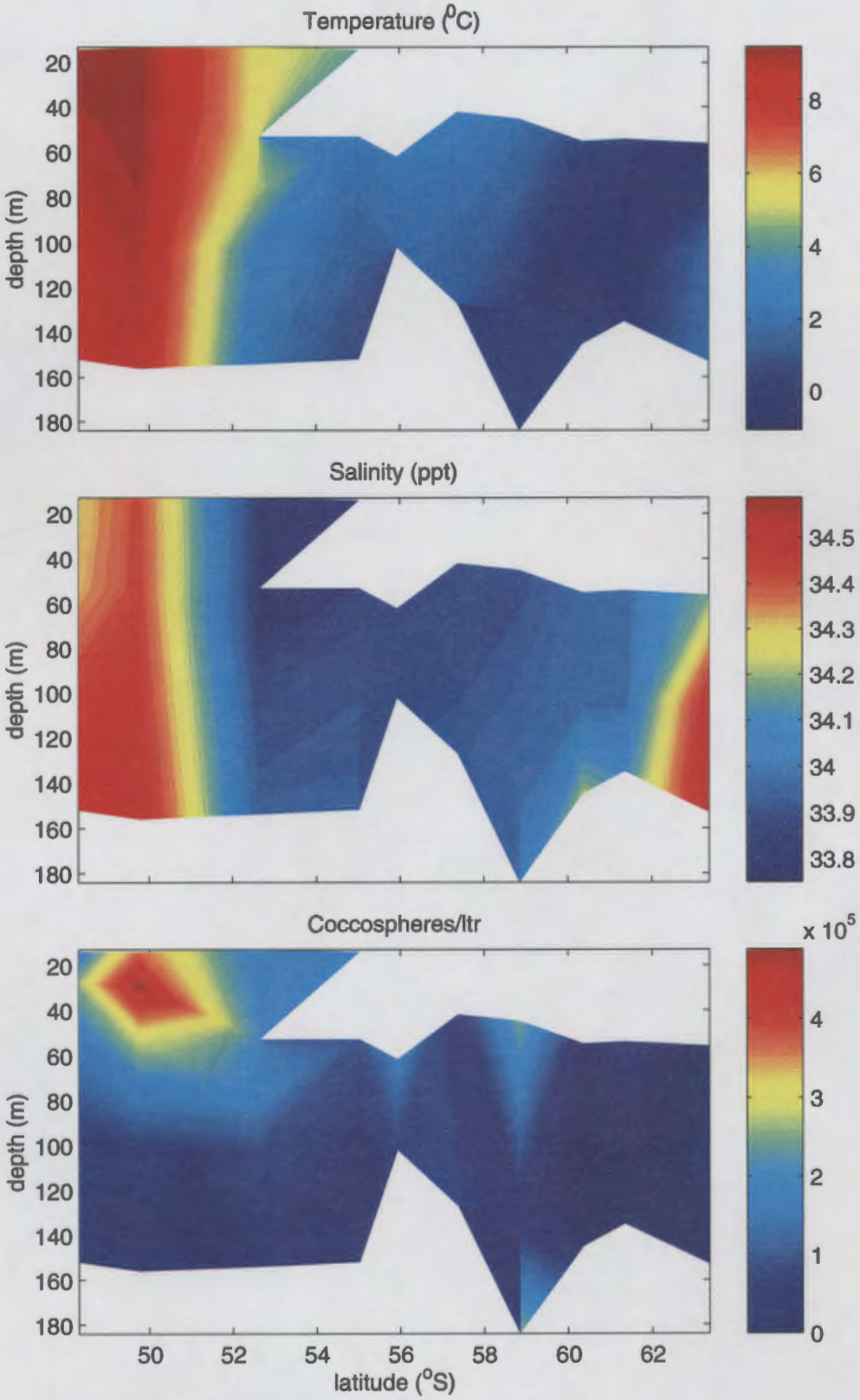


Fig 23 Temperature, salinity and cell density for austral summer 1994. Front locations – SAF between 51^0S and 52^0S; PF between 53^0S and 54^0S; AD at ~63^0S.

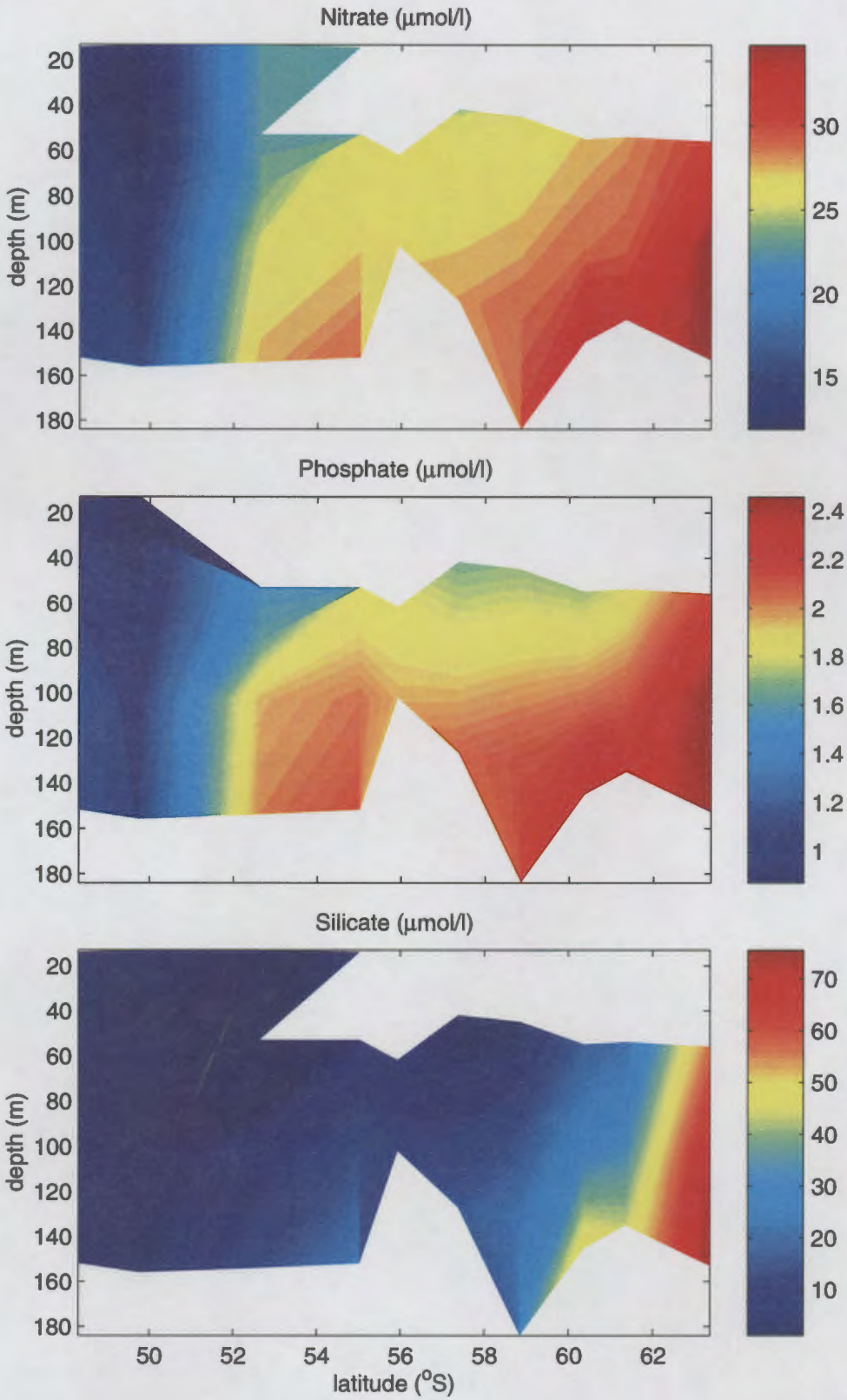


Fig 24 Nutrient data for austral summer 1994.
Front locations – SAF between 51^{0}S and 52^{0}S; PF between 53^{0}S and 54^{0}S; AD at ~63^{0}S.

higher minimum temperatures for *C. leptoporus*, *G. ericsonii*, *G. muellerae*, *S. molischii* and *U. tenuis*.

	1	2	3	4	5	6	7
E. huxleyi		min. 0°C	min. 2°C	1°C to 30°C		photic zone	
'warm water'	8.3°C to 18.4°C						5°C to 30°C
'cold water'	-0.2°C to 15.7°C						1°C to 20°C
'polar' form	-0.2°C to 9.1°C						
C. leptoporus	5.4°C to 14.2°C	min. 11°C	min. 2°C	5°C to 30°C		upper to middle photic zone	8°C to 30°C
C. pelagicus			6°C to 14°C				6°C to 14°C
G. ericsonii				min. 12°C			14°C to 30°C
G. muellerae	10.3°C to 15.7°C	5°C to ?18°C	min. 14°C	12°C to 30°C	9°C to 10°C	upper to middle photic zone	
G. oceanica							18°C to 30°C
G. caribbeanica							5°C to 27°C
H. carteri							min. 16°C
O. fragilis						lower photic zone	equatorial to 19°C
P. sagittifera	11.8°C to -0.3°C	-1°C to 14°C			<0°C to 6°C		
R. clavigera		min. 13°C				upper photic zone	14° to 30°C
S. pulchra		min. 10°C					
S. molischii	8.6°C to 15.7°C	4°C to ?25°C		5°C to 27°C	9°C to 10°C		
S. nodosa	9.6°C to 15.7°C	min. 5°C		2°C to 27°C	9°C to 10°C		
Syracosphaera spp	8.5°C to 15.7°C				min. 6°C		
U. sibogae							min. 18°C
U. irregularis							min. 21°C
U. tenuis	18.4°C to 10.3°C		min. 16°C	13°C to 29°C		middle photic zone	12°C to 29°C

1 - Australian Sector of the Southern Ocean, surface to 200m; this study
2 - Norwegian-Greenland Sea, surface to 150m; Samtleben et al., 1995A
3 - South Atlantic surface waters; McIntyre and Bé, 1967
4 - Western North Atlantic, surface to 100m; Okada and McIntyre, 1979
5 - Norwegian-Greenland Sea, surface to 500m; Samtleben and Schröder, 1992
6 - Pacific Ocean, surface to 200m; Okada and Honjo, 1973.
7 - Pacific Ocean; McIntyre, Bé and Roche, 1970

Table 4. Comparison of temperature ranges for some living coccolithophores between this study and previous studies.

Emiliania huxleyi

E. huxleyi is the dominant species at all depths in each sample. Highest abundances were found at 49°S (CTD 21; 29m), north of the SAF for 1994 and at 41°S (HC001; 56m) north of the STF for 1995.

Four morphotypes of *E. huxleyi* were identified: the 'warm water' form (Plate 1; Fig. 1); the 'cold water' form designated Type X (Plate 1; Fig. 2); the 'polar' form (Plate 1; Fig. 3) designated Type Y; and, a severely dissolved form, designated Type Z (Plate 1; Fig. 4). Both 'warm water' and 'cold water' forms were found down to 49°S in 1995 (north of the SAF), with the 'polar' form absent north of 47°S for the same period. In general, the 'warm water' form dominates the 'cold water' form north of the STF with an exception at 41°S (HC001; 50m). This sample showed the highest cell densities for both morphotypes for 1995. The 'warm water' form was absent from the 1994 data (south of the STF).

Similarly, previous studies have identified a number of morphotypes of *E. huxleyi*, including a 'cold water' form and 'warm water' form (McIntyre and Bé, 1967; Nishida, 1986; Verbeek, 1989; Giraudeau et al., 1993; van Bleijswijk et al., 1991). The 'cold water' form is less calcified than its counterpart, where the 'T' elements on the distal shield are not connected (Plate 1; Fig. 2). The central area is either open or enclosed by thin lath-like plates and the proximal shield may show some 'slitting'. In comparison, the 'warm water' form is heavily calcified with 'T' elements joined, no slitting on the proximal shield and the central area filled with a heavy grill-like structure (Plate 1; Fig. 1). A third morphotype has been identified as a 'subantarctic' form (Okada and Honjo, 1973) or 'polar' form (Verbeek, 1989). This form (Plate 1; Fig. 3) shows reduced symmetry, is less calcified with 'T' elements incomplete and distorted, and the proximal shield often well separated into sections giving a 'fan-like' appearance.

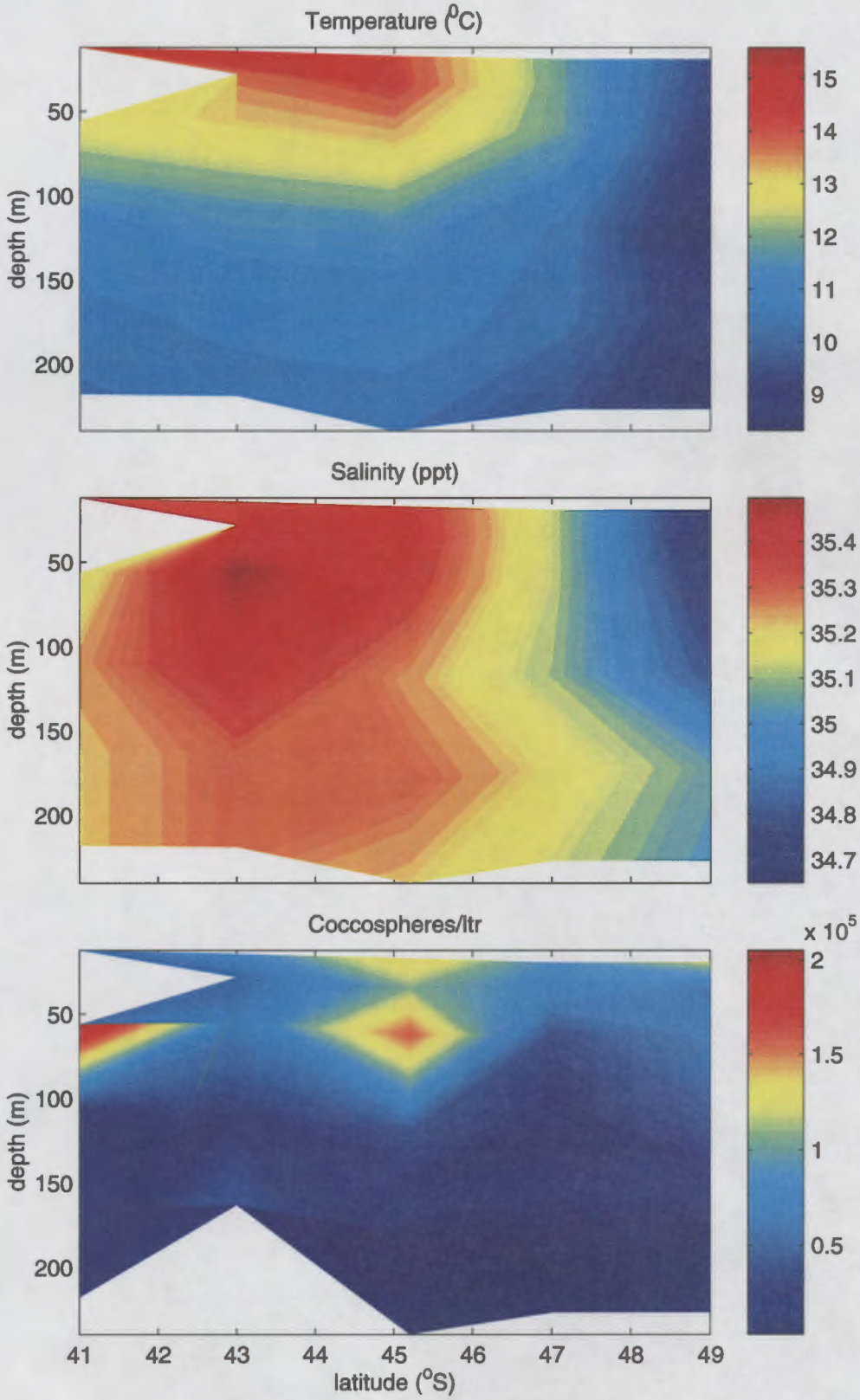


Fig 25 Temperature, salinity and cell density for austral summer 1995, excluding data from HC009.
Front location – STF between 46^0S and 47^0S.

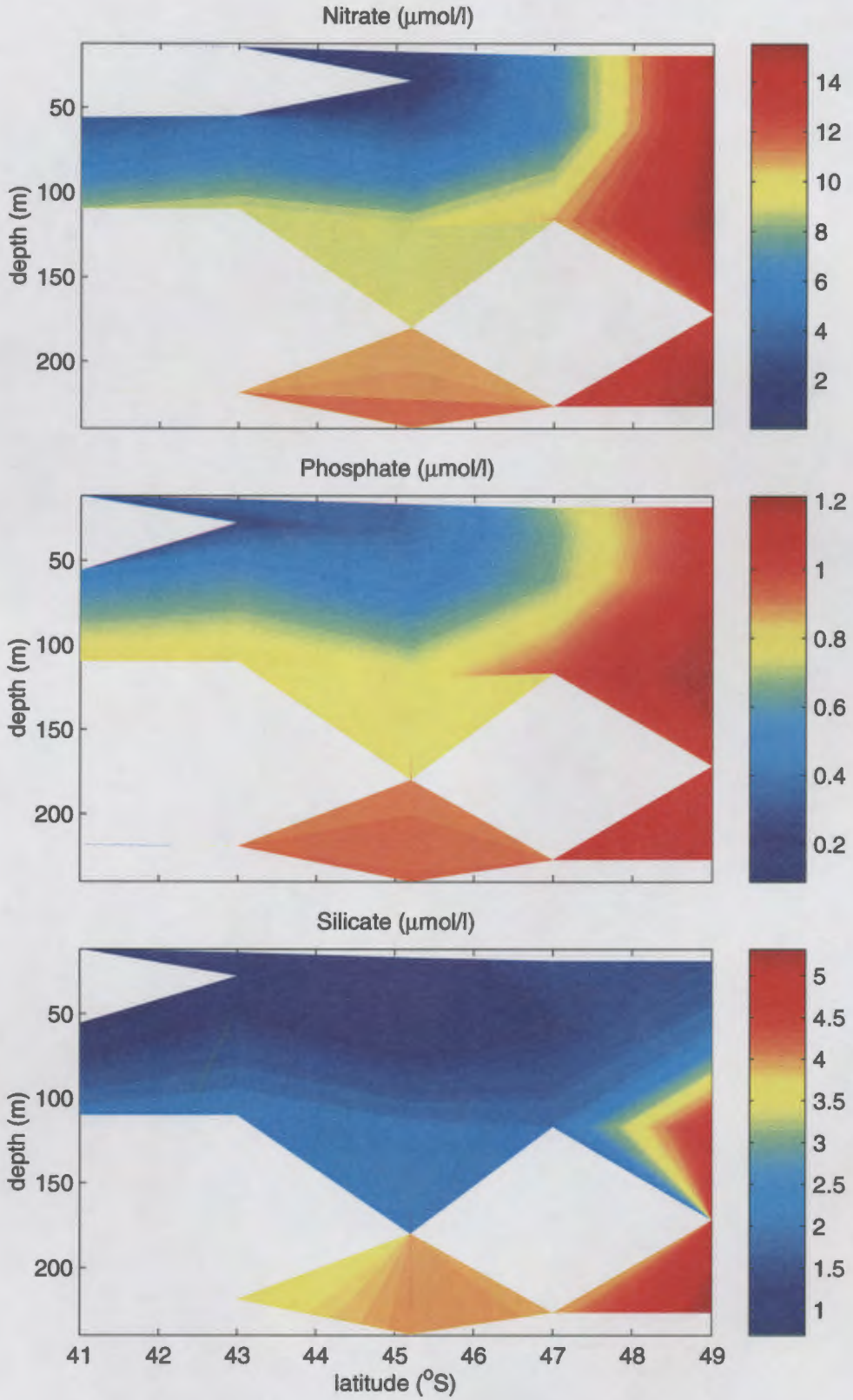


Fig 26 Nutrient data for austral summer 1995, excluding data from HC009.
Front location – STF between 46^0S and 47^0S.

Station No.	Water depth (m)	*E. huxleyi* -Type X %	*E. huxleyi* - Type Y %	*E. huxleyi* - Type Z %
CTD 16	14	16.78	48.95	34.26
48°18'	28	50.44	39.82	9.73
	53	66.12	14.51	20.96
	103	82.6	17.39	0
	152	25.28	24.13	50.57
CTD 21	14	98.35	0.54	1.09
49°45'S	29	97.66	0.77	1.55
	53	94.11	2.94	2.94
	103	75	20	5
	156	42.85	28.57	21.42
SUBANTARCTIC FRONT				
CTD 30	13	87.35	8.04	4.59
52°38'S	53	88.46	11.53	0
	77	76.1	23	0.88
	103	86.56	11.94	1.49
	154	82.6	17.39	0
POLAR FRONT				
CTD 37	14	56.58	40.31	3.1
55°01'S	53	12.32	60.27	27.39
	103	52.94	33.33	13.72
	152	64	32	4
CTD 39	13	77.45	14.7	7.84
55°55'S	62	91.02	6.41	2.56
	102	93.65	4.76	1.58
CTD 43	13	30.13	57.53	12.32
57°23'S	42	86.66	13.33	0
	127	30.26	18.42	51.31
CTD 47	14	85.71	12.38	1.9
58°51'S	45	25.58	72.09	2.32
	130	82.14	7.14	10.71
	184	25.23	73.83	0.93
CTD 51	13	50	25	25
60°21'S	55	0	20	80
	103	100	0	0
	145	0	0	0
CTD 54	13	45	55	0
61°20'S	54	81.48	18.51	0
	103	100	0	0
	135	33	67	0
ANTARCTIC DIVERGENCE				
CTD 59	14	0	0	0
63°21'S	56	0	0	0
	103	0	0	0
	153	0	0	0

Table 5 Relative abundance of *E. huxleyi* morphotypes for austral summer 1994; Type X - 'cold water' form; Type Y - 'polar' form; Type Z - severely dissolved.

The distal shield length, central area length, number of distal shield elements and structure of the central area for coccoliths of *E. huxleyi* 'cold

water' form, for 1994 (Appendix B3), were compared to previous studies and found to correlate with Type C defined by Young and Westbroek (1991) and the 'cold water' form of McIntyre and Bé (1967).

Data for 1994 showed the highest percentages for the 'cold water' form (Type X) south of the STF at ~49°S; for the 'polar' form (Type Y) south of the PF at ~58°S; and, for the severely dissolved form (Type Z) south of the PF at ~57°S (Table 5). Total percentages of the three morphotypes at each station (1994), without reference to depth, were plotted and showed highest percentages of Type X north of 56°S and for Type Y south of 56°S (Fig. 27).

Calcidiscus leptoporus

The highest percentages of *C. leptoporus* (Plate 1, Fig. 8; Plate 2, Fig. 1) were recorded in 1994 south of the STF (Appendix B1), with a temperature range of 5°C to 9°C. In 1995 *C. leptoporus* occurred at all stations in a north-south transect west of Tasmania with the exception of station HC009 within a temperature range of 8°C to 13°C. North of the STF *C. leptoporus* is a minor component of the assemblage where *U. tenuis*, *G. muellerae* and *Syracosphaera* sp. are found in higher abundances (Appendix B2). South of the STF *C. leptoporus* is the second most dominant species, after *E. huxleyi*, confirming this species preference for cooler transitional waters.

C. leptoporus collected in 1994, south of the STF, showed coccolith size variations between 3µm and 6µm, coccosphere sizes from 7µm to 11µm and number of distal shield elements from 15 to 24 (Table 6). These results are comparable to previously identified morphotypes, i.e, 'variety C', or 'Type C', found in subpolar waters (McIntyre et al., 1970; Kleijne, 1993) and 'Cluster I' in temperatures below 23.5°C (Knappertsbusch et al., 1997).

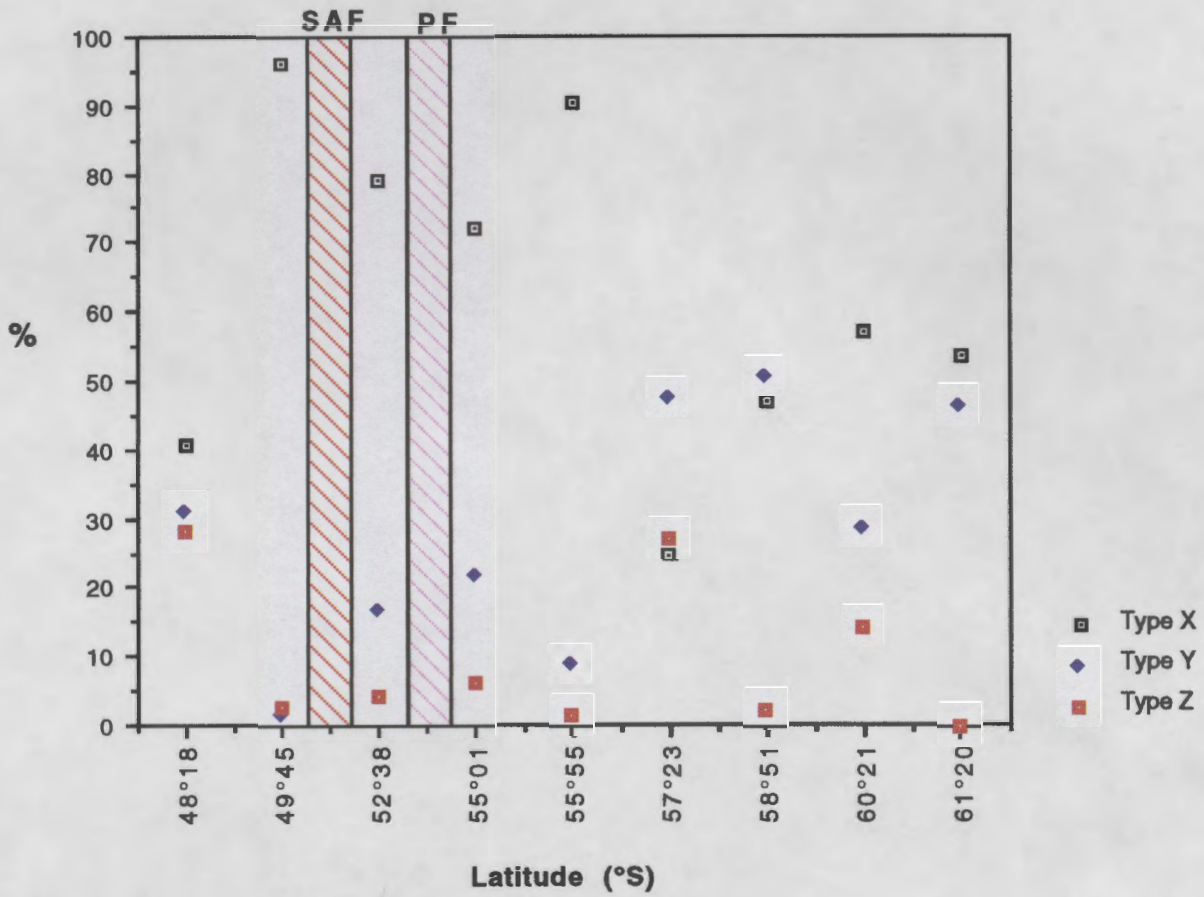


Fig. 27 Percentages of *E. huxleyi* morphotypes for austral summer 1994 with relation to latitude. Type X - 'cold water' form; Type Y - 'polar' form; Type Z - severely dissolved form.

Station No. Water Depth(m)	Number of elements per coccolith	Size of coccoliths (µm)	size of coccosphere (µm)	Relative % of coccospheres per 400 SEM screens
CTD-16				
10m	24, 21, 18, 21, 21	6, 4.2	11, 11.2, 9, 9	29%
25m	21, 19	3, 3.2	7, 7	17%
50m	18, 17, 18	4.8, 5	10	27%
100m	20, 15	5.5, 5.5	10	13%
150m	18, 20, 18, 19	5.5, 5.5, 5.5, 6, 5.5, 6	11, 9.2, 11	28%
CTD-21				
25m	24, 22,22	5.5, 5.5,5.4	11,11	5%
50m	20, 18, 24	5.8, 4.5, 7, 5, 5.5	10	8%
100m	0	0	0	0
150m	17,19,21	4.5,4.1,7,5.5	9,8.5,10.5	20%

Table 6 Measurements for *C. leptoporus*, austral summer 1994.

Umbellosphaera tenuis

Samples collected in 1995 showed *U. tenuis* (Plate 2; Fig. 3) was the second most dominant species north of the STF. Highest cell densities were found in the upper 50m with the exception of HC001 (41°S), where high cell density was recorded at 200m. South of the STF this species was recorded in smaller percentages down to 47°S. The temperature range for this species was documented between 10°C and 18°C. *U. tenuis* was not found in the 1994 data set.

Gephyrocapsa spp

G. muellerae (Plate 2; Fig. 5) was identified north of the STF in 1995 at all three stations, with a temperature range of 13°C to 15°C. Highest cell densities for were found at 41°S (HC001; 56m). Only one coccosphere of *G. ericsonii* was recorded, north of the STF at 44°S (HC009), east of Tasmania (Plate 2; Fig. 4). Species of gephyrocapsids were absent in the 1994 data set.

Syracosphaera spp

Members of this genus were found down to 49°S, north of the SAF (Appendix B1) in 1994. Only two species were identified with certainty,

with the remaining grouped under '*Syracosphaera* sp.' (Plate 2; Figs 6, 7). *S. molischii* (Plate 2; Fig. 8) was identified at 48°S (CTD 16; 152m) with a minimum temperature of 8°C. Highest cell densities for *S. nodosa* (Plate 3; Fig. 1) were found at the same location (14m) with a temperature minimum of 9°C.

Data for 1995 showed *Syracosphaera* spp as a major component of the assemblages (Appendix B2). Ten species were identified with highest cell densities for *S. nodosa* (45°S, 62m), followed by *S. molischii* (41°S, 12m) and *S. halldalii* (43°S, 12m). Both data sets showed a preference for the upper photic zone for *Syracosphaera* spp with a temperature range between 8°C and 15°C.

Coccolithus pelagicus

The identification of one coccosphere of *C. pelagicus*, motile phase (Plate 1; Fig. 5), at 41°S (HC001; 12m), is tentative and for this reason is not included in Appendix B2. *C. pelagicus* is a cold-water species considered to be extinct in the Southern Ocean.

Floral Assemblages

The five calcareous nannoplankton assemblages, all dominated by *E. huxleyi*, are identified on the abundance and diversity of subordinate species. Assemblage A, is considered to be a tropical assemblage with subtropical influences and is identified to the east of Tasmania (HC009); Assemblage B, to the west of Tasmania, north of the STF, is a subtropical assemblage with transitional influences (HC001, 2 and 4); Assemblage C, a transitional assemblage, was identified between the STF and SAF (HC005, 7 and 9; CTD 16 and 21); Assemblage D, is interpreted as a subantarctic assemblage between the SAF and PF (CTD 30); and, Assemblage E, an antarctic assemblage, is located between the PF and AD (CTD 37, 39, 43, 47, 51, and 54).

Assemblage A

Assemblage A is identified on the presence of tropical to subtropical species which were not found in the remaining assemblages (e.g., *A. unicornis, D. tubifera* and *Z. hellenica*). The region to the east of Tasmania is dominated by warm surface and subsurface waters associated with the poleward-flowing East Australian Current.

Assemblage A
Tropical to Subtropical

Austral summer, 1995	% of total coccospheres counted
Emiliania huxleyi 'warm water' form	39.34
Syracosphaera halldalii	9.83
Calciosolenia murrayi	9.28
Syracospheara nana	8.19
Alisphaera unicornis	3.82
Emiliania huxleyi 'cold water' form	3.27
Zygosphaera hellenica	3.27
Acanthoica quattrospina	2.73
Ophiaster hydroideus	2.73
Syracosphaera nodosa	2.73
Syracosphaera pulchra	2.73
Calicasphaera diconstricta	2.18
Umbellosphaera tenuis	1.64
Helicosphaera carteri	1.10
Gephyrocapsa muellerae	1.10
Syracosphaera molischii	1.10
Syracosphaera anthos	1.10
Discosphaera tubifera	1.10
Corisphaera gracilis	1.10
Zygosphaera marsilii	0.54
Syracosphaera histrica	0.54
Gephyrocapsa ericsonii	0.54

Table 7 Species identified in Assemblage A, north of the STF, east of Tasmania, for austral summer 1994, in order of dominance.

Assemblage B

Assemblage B is characterised by high diversity with a total of 26 species, dominated by the 'warm water' form of *E. huxleyi*. Subordinate species include *U. tenuis* and *Syracosphaera* sp. dominant in the upper photic zone, and *G. muellerae* dominant in the mid-photic zone. Assemblage B defines the subtropical to transitional zone west of Tasmania and north of the STF, a region influenced by the poleward-flowing Zeehan Current.

Assemblage B Subtropical to Transitional	
Austral summer, 1995	**% of total coccospheres counted**
Emiliania huxleyi 'warm water' form	46.75
Emiliania huxleyi 'cold water' form	38.27
Umbellosphaera tenuis	4.37
Syracosphaera molischii	2.54
Syracosphaera nodosa	1.52
Gephyrocapsa muellerae	1.39
Syracosphaera pulchra	0.82
Calcidiscus leptoporus	0.66
Syracosphaera sp.	0.63
Acanthoica quattrospina	0.63
Calciosolenia murrayi	0.63
Coronosphaera mediterranea	0.56
Syracosphaera corolla	0.43
Holococcolithophorid sp.	0.16
Ophiaster hydroideus	0.13
Michaelsarsia elegans	0.13
Helicosphaera carteri	0.09
Syracosphaera rotula	0.06
Syracosphaera ossa	0.06
Calyptrolithophora papillifera	0.03
Syracosphaera anthos	0.03
Pappomonas weddellensis	0.03

Table 8 Species identified in Assemblage B, north of the STF, for austral summers 1995, in order of dominance.

Assemblage C

Assemblage C, south of the STF, shows a marked reduction in diversity and abundance in 1994 compared to 1995. The 1995 data set shows Assemblage C differs to Assemblage B with the dominance *E. huxleyi* 'cold water' form, an increase in *C. leptoporus* and decreases in warm-water species including *U. tenuis* and *Gephyrocapsa* spp. Of the subordinate species, *Syracosphaera* sp. dominates the upper photic zone in 1995 and *C. leptoporus* in 1994.

Assemblage C Transitional	
Austral summer, 1994	**% of total coccospheres counted**
Emiliania huxleyi 'cold water' and 'polar' form	83.18
Calcidiscus leptoporus	14.82
Syracosphaera sp.	0.71
Syracosphaera nodosa	0.32
Cyrtosphaera cucullata	0.24
Ophiaster hydroideus	0.16
Coronosphaera mediterranea	0.16
Calciopappus rigidus	0.16
Syracosphaera molischii	0.08
Helicosphaera carteri	0.08
Acanthoica quattrospina	0.08
Austral summer 1995	
Emiliania huxleyi 'cold water' form	63.42
Emiliania huxleyi 'warm water' form	13.32
Syracosphaera nodosa	4.17
Syracosphaera molischii	2.88
Calcidiscus leptoporus	2.68
Emiliania huxleyi 'polar' form	2.08
Syracosphaera corolla	1.39
Syracosphaera pulchra	1.29
Acanthoica quattrospina	1.23
Holococcolithophorid sp.	1.19
Syracosphaera halldalii	0.99
Ophiaster hydroideus	0.99
Syracosphaera nana	0.89
Umbellosphaera tenuis	0.79
Cyrtosphaera cucullata	0.59
Syracosphaera sp.	0.49
Michaelsarsia elegans	0.39
Calciosolenia murrayi	0.20
Papposphaera sagittifera	0.20
Syracosphaera ossa	0.10
Syracosphaera histrica	0.10
Syracosphaera anthos	0.10
Sphaerocalyptra quadridentata	0.10
Helicosphaera carteri	0.10
Calciopappus rigidus	0.10
Polycrater galapagensis	0.10

Table 9 Species identified in Assemblage C, between STF and SAF for austral summers 1994 and 1995, in order of dominance.

Assemblage D

Assemblage D is monospecific assemblage of *E. huxleyi*, comprising the 'cold water' and 'polar' forms with the exception of one coccosphere of *C. leptoporus* at 53°S (CTD 30). Cell density and diversity is greatly reduced in this assemblage compared to Assemblage C.

Assemblage D Subantarctic	
Austral summer, 1994	**% of total coccospheres counted**
Emiliania huxleyi 'cold water' and 'polar' form	99.76
Calcidiscus leptoporus	0.24

Table 10 Species identified in Assemblage D, between the SAF and PF, for austral summer 1994, in order of dominance.

Assemblage E

Assemblage E is defined on the presence of semi-calcified polar species in the otherwise monospecific assemblage of *E. huxleyi*. The semi-calcified species include *Papposphaera sagittifera* (Plate 3; Fig. 3), *Wigwamma antarctica, Wigwamma triradiata* and *Papposphaera obpyramidalis* (Plate 3; Fig. 4), which record highest numbers at 61°S (CTD 54).

Assemblage E Antarctic	
Austral summer, 1994	**% of total coccospheres counted**
Emiliania huxleyi 'cold water' and 'polar' form	99.54
Papposphaera sagittifera	0.22
Papposphaera obpyramidalis	0.07
Wigwamma antarctica	0.07
Wigwamma triradiata	0.07

Table 11 Species identified in Assemblage E, south of the PF, for austral summer 1994, in order of dominance.

South of the Antarctic Divergence (CTD 59) samples were devoid of coccolithophores. However, they contained abundant siliceous cysts, known as parmales (Booth and Marchant, 1987) including *Tetraparma*

pelagicus (Plate 3; Fig. 6), *Triparma columacea* (Plate 3; Fig. 7) and *Triparma laevis* (Plate 3; Fig. 8).

C. Discussion

Standing Crop

The overall decrease in abundance and diversity of coccolithophores with increasing latitude corresponds to decreases in temperature and increases in nutrients. Decreases of coccolithophores in a poleward direction in this region have been noted previously (Nishida, 1986).

The depth of approximately 50m, north of the STF, appears to be the optimum for production compared to 10m to 30m depth, south of the STF (Figs 23, 25). Stations to the north of the STF are under the influence of poleward-flowing, warm surface waters. The higher temperatures (14.2°C to 18.4°C) and salinities (35.38‰ to 35.64‰) associated with these surface waters restrict production of coccolithophores in the upper 50m, particularly evident at HC009 (Fig. 19; Table 3). This station records the highest salinities and temperatures and lowest cell densities at all depths, and is clearly associated with a separate, warmer water mass, evident on the remote sensing image (Fig. 22). An exception to this pattern is found at 43°S (HC002) with highest productivity in surface waters (14m) with a temperature of 15°C and salinity of 35.34‰. The region to the west of Tasmania is a mixing zone of warm surface waters to the north and colder surface waters the south, which can be seen on the remote sensing image, particularly at the time of sampling for HC002 (Fig. 22). This may explain the anomalies in productivity and associated physico-chemical properties in this region.

South of the STF the highest cell density was recorded in the upper 30m. An exception to this, between the SAF and PF (53°S), showed highest cell density at 77m with a corresponding temperature of 4.7°C (Table 2). The assemblage at 77m may have been transported to that depth via the influx

of an adjacent water mass, as documented in previous studies (Giraudeau et al., 1993), or by the sinking of a surface water assemblage at the same location. Salinity, temperature and nutrient levels do not indicate the presence of a separate water mass at 77m compared to overlying surface waters and the assemblage at this location is interpreted as a sinking assemblage.

Cell densities decreases at depth in association with increases in nutrients, particularly nitrate and phosphate, and decreases in temperature. These changes are identified at approximately 50m to 60m north of the STF and approximately 100m south of the STF (Tables 2, 3). Calcareous nannoplankton are considered to prefer nutrient depleted waters (Houghton, 1988; Giraudeau et al., 1993; Brand, 1994) and the increase of nitrate and phosphate at depth, coupled with the reduction in temperature and light intensity would account for the decrease in productivity at depth.

Across the PF, the drop in cell density is also associated with a drop in temperature and increases in nutrients. The same pattern is found between 59°S (CTD 47) and 61°S (CTD 51). The remote sensing image shows these two stations are associated with separate water masses (Fig. 21).

Temperature

Clearly, temperature is a major factor controlling the abundance and diversity of coccolithophores. These data show a minimum temperature of approximately 2°C is required for coccolithophore production in surface and subsurface waters. Maximum cell densities for each station were recorded between temperatures of 4°C and 13°C. Temperatures outside these parameters greatly reduce the abundance and diversity of coccolithophores. A decrease of approximately 2°C corresponds to changes in assemblages in surface waters, e.g., 2.43°C across the STF, 4°C across the SAF and 1.38°C across the PF are associated with decreases in

cell density. South of the AD the SST is approximately 1°C , too low for coccolithophore production (with the possible exception of semi-calcified polar species). The degree of change in cell densities corresponds to the degree of change in temperature, e.g., the decreases in cell density and temperature across the STF and SAF compared to the PF.

Not all reductions in cell densities correspond to reduction in temperature (Table 2). For example, at 49°S (CTD 21) a sizable reduction in cell density at 53m corresponds to a decrease of 0.09°C. Surface water temperatures at 57°S (CTD 43) are higher than the station equatorward, although the cell density is lower. Cell density is found to increase in surface waters at 58°S (CTD 47) compared to the station equatorward, although the temperature decreases. At depth (14m to 45m), this station shows a decrease in cell density with minimal temperature change. It is evident factors other than temperature contribute to cell density and distribution of coccolithophores.

The low temperatures (-0.2°C, 0.3°C) recorded in conjunction with high cell densities at depths of 77m or more indicated these assemblages are not *in situ*, and have been transported from adjacent water masses or are sinking assemblages from surface waters above. At the stations where high cell density occurs at depths of 77m or more, the SST is between 2°C and 4°C, recognised within the limits of calcareous production for living calcareous nannoplankton (McIntyre and Bé, 1967). The SST, coupled with no physico-chemical signatures for a separate water mass at depth, suggests the high cell densities at depth are sinking assemblages from overlying surface waters.

Salinity

The variation in salinity levels in a vertical profile is interpreted as instability due to mixing of waters within the photic zone (Tables 2, 3). This instability is evident in the region north, and immediately south, of the STF (HC001, 2, 4 and 5) where variability in the vertical profile differs

to the regular increase with depth recorded for stations to the south (HC007 and all CTD stations). In contrast, HC009 north of the STF shows a regular decrease of salinity with depth, reflecting the poleward-flowing tropical water mass.

In general, salinity decreases in a poleward direction across frontal zones in surface waters, with the exception of the PF which shows a minor increase. It is possible this indicates upwelling of more saline waters immediately south of the PF, a region which has been previously identified with upwelling waters (Allanson et al., 1981).

The changes recorded in salinity levels appear to have little effect on the overall abundance and diversity of calcareous nannoplankton. This is not surprising, as the main component of the assemblages, *E. huxleyi*, is a eurihaline species, which tolerates a wide range of salinities.

Nutrients

Nitrate, Phosphate and Silicate.

Increases in nitrate, phosphate and silicate levels were found to increase in a poleward direction, with further increases recorded in a vertical profile below 50m depth for most stations (Figs 24, 26). These increase are coupled with a reduction in cell density and it is considered they directly effect production of coccolithophores, in particular, high silicate concentrations south of the PF. Experiments adding silicate to surface waters found the production of *E. huxleyi* was inhibited, and when no additional silicate was added, this species formed blooms in the same environment (Egge and Aksnes, 1992). This demonstrates dissolved silicate directly effects coccolithophore production, rather than solely promoting the production of siliceous phytoplankton which then out-compete coccolithophorids.

An exception to the standard pattern of increased silicate and reduced coccolithophores is found at 43°S (HC002), where a reduction is recorded

for both silicate and coccolithophores (Table 3), further suggesting mixing of waters at this location.

Species

Emiliania huxleyi

E. huxleyi was present at ~61°S, immediately north of the Antarctic Divergence. Similarly, previous studies have identified *E. huxleyi* at 62°S and 65°S (Hasle, 1960; McIntyre and Bé, 1967) with highest abundances recorded adjacent to the STF and PF (Eynaud et al., in press; Nishida, 1986).

The 'warm water' morphotype of *E. huxleyi* showed highest cell densities north of the STF at depths >160m where it comprised >80% of the total assemblage and is the only *E. huxleyi* morphotype present in the tropical to subtropical water mass to the east of Tasmania. Conversely, the 'cold water' morphotype is dominant south of the STF in the subantarctic water mass. These results suggest water temperature may be an important factor controlling the distribution and abundance of these two morphotypes. Previous studies have recorded both forms in warm waters north of the STF (Verbeek, 1989; Hiramatsu and De Deckker, 1996) and in the California Current (Winter, 1985).

The mixing of surface waters to the northwest of Tasmania (Newell, 1961), may explain the unexpected high cell densities of the 'cold water' form at 41°S (HC001; 56m). South of the STF the 'cold water' form dominates the assemblage for austral summer 1995, as found in previous studies in the same region (Hiramatsu and De Deckker, 1996). These results indicate the preservation of the 'warm water' form in sediments could be used to reconstruct the paleo-position of the STF in this region, noted previously (Hiramatsu and De Deckker, 1996).

The 'polar' form (Type Y) was recognised in both transects of this study. The increase of this morphotype south of 55°S (Fig. 27) suggests a

relationship with low temperatures. First order malformation due to low temperature or changes in nutrient levels has been proposed for the 'polar' form, resulting in the production of irregular 'T' structures; rather than dissolution, which would show dissolution of both shields (Kleijne, 1990). However, the irregular appearance of 'T' elements could result from dissolution of the central ring, causing the distal shield to collapse and the irregular displacement of 'T' elements, i.e., a 'collapsed coccolith morphotype' (Young, 1992).

The presence of the 'polar' form identified at 47°S (HC005) and 49°S (HC007) in relatively warm waters found no correlation with the depletion of nitrate levels, as suggested in previous studies (Okada and Honjo, 1973; Kleijne, 1990), further indicating this morphotype may be the result of dissolution. Malformation of coccospheres in nutrient-rich subsurface waters has been previously documented from the Benguela upwelling system, although this was interpreted as transportation of malformed species into the region (Giraudeau et al., 1993).

Calcidiscus leptoporus

C. leptoporus (Plate 1, Fig. 8; Plate 2, Fig. 1) is considered to be a cold-water species with its absence in the pelagic environment at HC009 interpreted as the result of high water temperatures. Previous studies in the same region have suggested the absence of this species is associated with the close proximity of the coastline (Hiramatsu and De Deckker, 1996).

Low abundances of *C. leptoporus* north of the STF and high abundances south of this front agrees with previous records in the Southern Ocean (Nishida, 1986; Eynaud et al., in press; McIntyre and Bé, 1967). In contrast, Verbeek (1989) found this species only in samples to the north of the STF, south of Africa, while Hiramatsu and Deckker (1996) found this species did not vary in abundance across the STF, where it is recorded as the second most dominant species in all samples. It is possible this species is subject to seasonal productivity, which may account for the differences in regional studies.

Previous records have recorded this species with a minimum temperature of 8°C in the South Atlantic where it occupies the same environmental niche as that of *C. pelagicus* in the Northern Hemisphere (McIntyre and Bé, 1967). It is suggested *C. leptoporus* has recently (in geological terms) taken over the niche left vacant by *C. pelagicus* in the Southern Hemisphere. Although *C. leptoporus* is considered to be a cold-water species, it is not entirely confined to such waters. In the mid-Pacific *C. leptoporus* has been recorded as a minor component of assemblages either side of the equator (Honjo and Okada, 1974) and in the tropical belt between 11°N and 17°S (Knappertsbusch et al., 1997).

Umbellosphaera tenuis

The data for *U. tenuis* shows highest cell densities north of the STF for 1995 with a poleward limit at 47°S. Similarly, previous studies have identified *U. tenuis* as the second most dominant species to 41°S in the South Atlantic (McIntyre and Bé, 1967); as the most abundant in the Agulhas Front, decreasing poleward and absent south of the SAF (Eynaud et al, in press); absent north of 41°N in the Pacific Ocean (Okada and Honjo, 1973); and, absent in the North Atlantic, north of 63°N (Samtleben, et al., 1995a; 1995b), confirming this species preference for subtropical to transitional waters.

In the same region as this study, *U. tenuis* was found in low abundances at approximately 43°S compared to high abundances of *U. irregularis* down to 46°S (Hiramatsu and De Deckker, 1996). This is unusual as *U. irregularis* was not found in this study and is a delicate form preferring tropical to subtropical waters, compared to the more robust *U. tenuis* (Okada and Honjo, 1973). In the South Atlantic, the southern limit for *U. irregularis* is restricted by the 21°C isotherm (McIntyre and Bé, 1967).

The increase of *U. tenuis* at 218m at 41°S (HC001) corresponds with an increase in *E. huxleyi* 'warm water' form at the same depth and is interpreted as a sinking assemblage from the overlying surface water.

Gephyrocapsa spp

Two *Gephyrocapsa* spp were identified in austral summer 1994 and 1995, *G. ericsonii* at HC009 and *G. muellerae* at all stations north of the STF, indicating a preference for warmer waters for these two species. *G. ericsonii* is considered to have a similar biogeographic zone to *G. oceanica* (McIntyre and Bé, 1967) with a temperature range between 12°C and 27°C (Okada and McIntyre, 1979). The low abundance of these two species may reflect seasonal production as they have been previously identified as far south as the PF, south of Australia (Nishida, 1986) and south of the STF with a SST minimum of 11°C (Hiramatsu and Deckker, 1996), compared to a minimum of 13°C recorded in this study.

In the Northern Hemisphere *G. muellerae* is considered to prefer transitional waters (Samtleben and Schröder, 1990; Samtleben et al., 1995a) and has been recorded with a temperature range of 5°C to 14°C in the Norwegian-Greenland Sea (Samtleben et al., 1995a). The difference of poleward extent and minimum temperatures between the two hemispheres reflects the different hydrographic regimes, where poleward-flowing, warm-water currents reach higher latitudes in the Northern Hemisphere enhancing seasonality, compared to the Southern Hemisphere, where the STF inhibits the poleward-flow of warm-water currents to high latitudes.

Syracosphaera spp

Syracosphaera spp are restricted to north of 49°S, indicating a preference for warmer waters. The data for 1995 recorded 10 species with a number specimens difficult to identify to species level (Plate 2; Figs 6, 7). Highest cell densities were recorded for *S. molischii* (Plate 2; Fig. 8) with a temperature minimum of 8.6°C, followed by *S. nodosa* (Plate 3; Fig. 1) with a minimum of 9.6°C, and *S. pulchra* (Plate 3; Fig. 2) with a minimum of 9.3°C. The poleward extent of *S. molischii* in 1994 was 48°S and for *S. nodosa*, at 49°S, with respective temperature minimums of 8.6°C and 9.6°C (Table 4).

In the same region, *Syracosphaera* spp have been previously recorded as the second most dominant species after *E. huxleyi* with highest cell densities at 43°S (Hiramatsu and Deckker; 1996); and, *S. pulchra* has been found at the PF (Nishida, 1986) and within transitional and subantarctic regions (McIntyre and Bé, 1967; Nishida, 1986; Verbeek, 1989; Eyaund et al., in press). In comparison, in the Northern Hemisphere, *Syracosphaera* spp have been found at 58°N in the North Atlantic (Knappertsbusch and Brummer, 1995) and 41°N in the Pacific Ocean (Okada and Honjo, 1973) with temperature minimums of 3°C in the Norwegian Sea (Samtleben et al., 1995a). In the North Atlantic a minimum temperature of 2°C for *S. nodosa* and 5°C for *S. molischii* was recorded in the North Atlantic (Okada and McIntyre; 1979).

Coccolithus pelagicus

The absence of living *C. pelagicus* in the Southern Ocean has been explained by its recent extinction in this region (McIntyre and Bé, 1967). The current temperature range for living *C. pelagicus* in the Northern Hemisphere is 6°C to 14°C, a temperate region which does not always exist in the Southern Hemisphere where subtropical waters often run into subpolar waters (McIntyre et al., 1970). This restricted niche in the Southern Hemisphere may have disappeared during the post-glacial warming event identified at 8 ka, when subtropical waters migrated poleward (McIntyre et al., 1970). In contrast, some studies have found living *C. pelagicus* in the Southern Hemisphere, restricted to the upwelling system off Namibia (Giraudeau et al. 1993), a few specimens northwest of Tasmania (Hallegraeff, 1984), the motile phase south of Australia (Nishida, 1986; this study) and a few in the wharf area of Hobart (Hallegraeff pers comm.).

Closer examination of these occurrences suggest *C. pelagicus* is restricted to upwelling regions in the Southern Hemisphere, north of the STF. The introduction of exotic species to the waters in the region of the Hobart wharf area via ballast water from the Northern Hemisphere is common

(Williams et al., 1988) and the presence of *C. pelagicus* in these waters is considered to reflect this process rather than indicate its natural environment. The region to the southwest of Australia occasionally upwells and it is possible *C. pelagicus* lives in this environment prior to its transportation to the south and then east via the east-flowing Leeuwin Current, which deflects poleward (Cresswell and Golding, 1980) forming the Zeehan Current (Baines et al., 1983) along the northwest coast of Tasmania (Fig. 18). This path of transportation has been noted previously where tropical and subtropical fauna are carried from west of Australia to south of Australia (Morgan and Wells, 1991) and is supported by the identification of *Syracosphaera apsteinii* (a tropical coccolithophorid species) interpreted as transported via the same current (Hallegraeff, 1984).

Alternatively, seasonal production of *C. pelagicus* may also play a role in the record of this species in the Southern Hemisphere, as studies in the northwest Pacific Ocean show production is restricted to spring and/or autumn in the waters of the subpolar zone (Broerse, 1997). Records in the Southern Hemisphere record austral summer sampling which would not show spring or autumn production.

Floral Assemblages

Assemblage A

This assemblage is identified as a tropical assemblage with subtropical influences based on the presence of warm-water species, including *D. tubifera* which is limited poleward by the 16°C isotherm (McIntyre and Bé, 1967). The temperature and salinity levels are much higher than stations to the west of Tasmania at the same latitude, depicting a separate water mass at this location, the poleward-flowing tropical waters associated with the East Australian Current. This current originates in tropical waters and follows the east coast of Australia as far south as the east of Tasmania (Rochford, 1957).

Assemblage B

Assemblage B is interpreted as a subtropical assemblage with transitional influences, where the 'warm water' form of *E. huxleyi* dominates, the 'cold water' form is present and *U. tenuis* is the second most dominant species. Some species show depth preference in this assemblage, e.g., *U. tenuis* in the upper photic zone, some *Syracosphaera* spp in the upper to mid-photic zone and *G. muellerae* in the mid-photic zone. An exception to this is the high abundance of *U. tenuis* at 218m (41°S; HC001), indicating mixing of surface and subsurface waters. The location of Assemblage B to the west of Tasmanian is under the influence of the poleward-flowing Zeehan Current (Fig. 19), bringing warmer waters into the region and is a zone of mixing between subtropical surface waters to the north and transitional surface waters to the south. The temperature and salinity for this region are less than recorded for the east of Tasmania, identifying a separate water mass which does not reflect a tropical influence.

Assemblage B is similar to previously described assemblages including the 'Subtropical Assemblage' south of Australia dominated by *E. huxleyi* 'warm water' form and *U. tenuis* (Nishida, 1986); the 'Transitional Zone' in the South Atlantic which includes *U. tenuis*, *G. ericsonii*, *G. oceanica*, *C. leptoporus* and *E. huxleyi* (McIntyre and Bé, 1967); and, the assemblage identified between the Agulhas Front and the STF south of Africa dominated by *E. huxleyi* and *U. tenuis* (Eyaund et al. in press). Assemblage B is not comparable to previously identified flora zones in the Northern Hemisphere, i.e., six in the North Pacific, (Okada and Honjo, 1973) and three in the Norwegian-Greenland Sea (Samtleben and Schröder, 1992).

semi-calcified species, which have been previously identified in the Weddell Sea adjacent to Antarctica (Thomsen et al., 1988), record highest diversity and abundance at the most poleward station (CTD 54). Of the four semi-calcified species identified, *P. sagittifera* is common in the Norwegian-Greenland Sea (Samtleben and Schröder, 1992) and the remaining three (*P. obpyramidalis, W. antarctica, W. triradiata*) are recorded here for the first time in regions other than the Weddell Sea. The low abundance of coccospheres in this region (Appendix B1) is attributed mainly to low surface water temperatures and higher nutrient levels, considered to effect the productivity of coccolithophores in the water column.

South of the Antarctic Divergence (south of 62°S) low temperatures and high levels of nutrients, particularly nitrate and silicate are considered to inhibit the production of coccolithophores and enhance the production of siliceous phytoplankton. At approximately 63°S to 64°S parmales, a siliceous phytoplankton (Booth and Marchant, 1987), dominates the flora with diatom-dominated communities to the south of 64°S. Similarly, parmales have previously been found abundant south of Australia, at 64°S (Nishida, 1986) and at 50°N in the North Pacific (Nishida, 1979).

D. Summary

Standing Crop

In general, cell density and diversity decrease in a poleward direction corresponding to a decrease in temperature and salinity, and increases of nitrate, silicate and phosphate. Of these five parameters, temperature appears to be the most significant factor effecting the calcareous nannoplankton assemblages. The minimum temperature for coccolith production is approximately 2°C with major changes effecting the assemblages where the temperature changes by approximately 2°C. These changes are particularly apparent across the three frontal zones of the STF, SAF and PF, and the Antarctic Divergence. Decreases in temperature

and cell density coupled with increases of nutrients are found between 59°S (CTD 47) and 61°S (CTD 51) and may indicate a previously unrecognised front, or reflect the presence of a cold water cell at 61°S. The remote sensing imagery supports the second explanation, showing the station at 61°S associated with lower SST.

Increases in dissolved silicate is considered to have a direct effect on calcareous nannoplankton production, as well as enhancing the productivity of siliceous phytoplankton (e.g., parmales and diatoms) which would dilute the calcareous nannoplankton assemblages. The sudden increase of silicate at the Antarctic Divergence coupled with increase in phosphate and nitrate and a SST of 0.8°C inhibits the production of calcareous nannoplankton.

The depth of maximum production is greater north of the STF (50 to 60m) compared to south of the STF (25m). This is interpreted as suppression of production in surface waters north of the STF related to higher temperatures and possibly increased light levels. Exceptions to this pattern are found at HC002 north of the STF, with high cell densities at 14m; and, at CTD 30 south of the STF, with high cell densities at 77m. High cell densities recorded at depths greater than 77m are associated with low temperatures (<0.3°C), too low for coccolithophore production, and these assemblages are interpreted a sinking assemblages from surface waters above. These assemblages can not be interpreted as transported assemblage from adjacent water masses, as the physico-chemical parameters do not indicate different water masses. The higher cell density recorded at 14m for station HC002, north of the STF, is considered to be the result of mixing of different surface waters in this region.

Species

Four morphotypes of *E. huxleyi* were identified, 'warm water' form; Type X ('cold water'); Type Y ('polar'); and, Type Z. The 'warm water' form is dominant north of the STF and absent south of 49°S; the 'cold water'

dominates the assemblages to the south of the STF and it is possible these two morphotypes are controlled to some extent by temperature. Measurements of Type X show a good comparison to the 'cold water' morphotypes described by previous authors. Types Y ('polar' form) and Z (severely dissolved form) of this study are considered to be the result of dissolution. Type Y increases in abundance with increasing latitude, suggesting a relationship between distribution and temperature.

C. leptoporus records the highest cell density south of the STF to 52°S and is absent in the tropical waters at HC009, confirming its preference for cooler waters. Previously recorded absences of this species in the same region have been attributed to its preference for pelagic versus neritic environments. In contrast, the results of this study suggest temperature is the main factor controlling distribution of this species in this region.

Syracosphaera spp are identified as preferring subtropical to transitional water masses of the upper to mid-photic zone with highest cell densities north of the STF. *Gephyrocapsa* spp are interpreted as preferring tropical (*G. ericsonii*) to subtropical (*G. muellerae*) environments. Members of this genus may be influenced by seasonal production in this region, indicated by the absence of *G. oceanica* and the low numbers of *G. muellerae* and *G. ericsonii.*

This study found no evidence to support the existence of *C. pelagicus* in the living communities of the Southern Ocean, however, there is some evidence to suggest it is associated with periodic upwelling off the southwest coast of Australia, and may be transported as far east as northwest Tasmania via surface water currents.

Floral Assemblages

Five floral assemblages based on abundance and species content were recognised in this study, i.e., Assemblage A, to the east of Tasmania north of the STF, identified as a tropical assemblage; Assemblage B, to the west

of Tasmania, north of the STF, identified as a subtropical assemblage; Assemblage C between the STF and SAF, a transitional assemblage; Assemblage D between the SAF and PF, a subantarctic assemblage; and Assemblage E between the PF and the Antarctic Divergence, identified as the antarctic assemblage.

Of the three major oceanic fronts in the Australian Sector of the Southern Ocean, the STF has the greatest effect on calcareous nannoplankton assemblages, followed by the SAF, and to a lesser degree, the PF which appears to have a minimal effect. The Antarctic Divergence defines the southern limit of the living coccolithophores in this sector of the Southern Ocean.

The results of this study are based on a samples collected during the austral summer season which do not reflect seasonal production in this region. Consequently, caution should be employed in the interpretation of biogeographic zones based on the results of this study.

Chapter Five Surface Sediments

A. Introduction

Calcareous nannoplankton are one of the main components of carbonate ooze which covers approximately 50% of the sea-floor of the world's oceans (Kennett, 1982; Roth, 1994). One study on $CaCO_3$ flux has shown the flux contains 64% coccoliths, 29% planktonic foraminifera and 7% pteropods (Honjo, 1976). Little research has been carried out on coccolithophore assemblages in the surface sediments of the Australian Sector of the Southern Ocean, however, research from the high latitudes of the Northern Hemisphere is, in part, comparable to this study (Gard and Backman, 1990; Kleijne, 1991; Gard and Crux, 1991; Baumman and Matthiessen, 1992; Samtleben and Schröder, 1994; Samtleben et al., 1995a, 1995b; Knappertsbuch and Brummer, 1995).

The objectives of this section of the study are threefold: (1) determine species abundance and diversity of calcareous nannoplankton in the surface sediments; (2) compare those data with the distribution pattern of living populations in overlying surface and subsurface water; and, (3) discuss the differences between the two data sets with regard to diagenetic and oceanographic processes.

Materials and Techniques

Surface sediment samples were selected on the basis of their potentially high carbonate content, i.e., from areas which are considered to be above the calcite lysocline in this region. The modern calcite lysocline, located above the CCD, has been estimated at about 4300m in the Southern Ocean (Kolla et al., 1976; Howard and Prell, 1994).

A total of 45 surface sediment samples were collected between 41°S and 58°S (Table 1). Sample locations are shown on Figure 19 (South Tasman Rise) and Figure 28 (Southern Ocean). Samples pre-fixed with 'MD' were supplied by the Department of Geology and Oceanography, at the University of Bordeaux, with the remaining samples provided by the Australian Geological Survey Organisation (Exon et al., 1995).

In order to determine the preservation of calcareous nannoplankton between the living communities in the water column and the sediments below, it is necessary to identify recent surface sediments that are representative of the living community. In this study, sediments dominated by *E. huxleyi*, i.e., 73 ka or younger (Thierstein et al., 1977), are considered to represent the present-day living community.

Two counts were made for surface sediment samples. First, to find surface sediments with a majority of *E. huxleyi* over *G. muellerae*. This first count ('main species') counted all *Gephyrocapsa* spp and *E. huxleyi* individually, and all other subordinate species as a single group, where the percentages reflect those of the total assemblage (Appendix A2). For

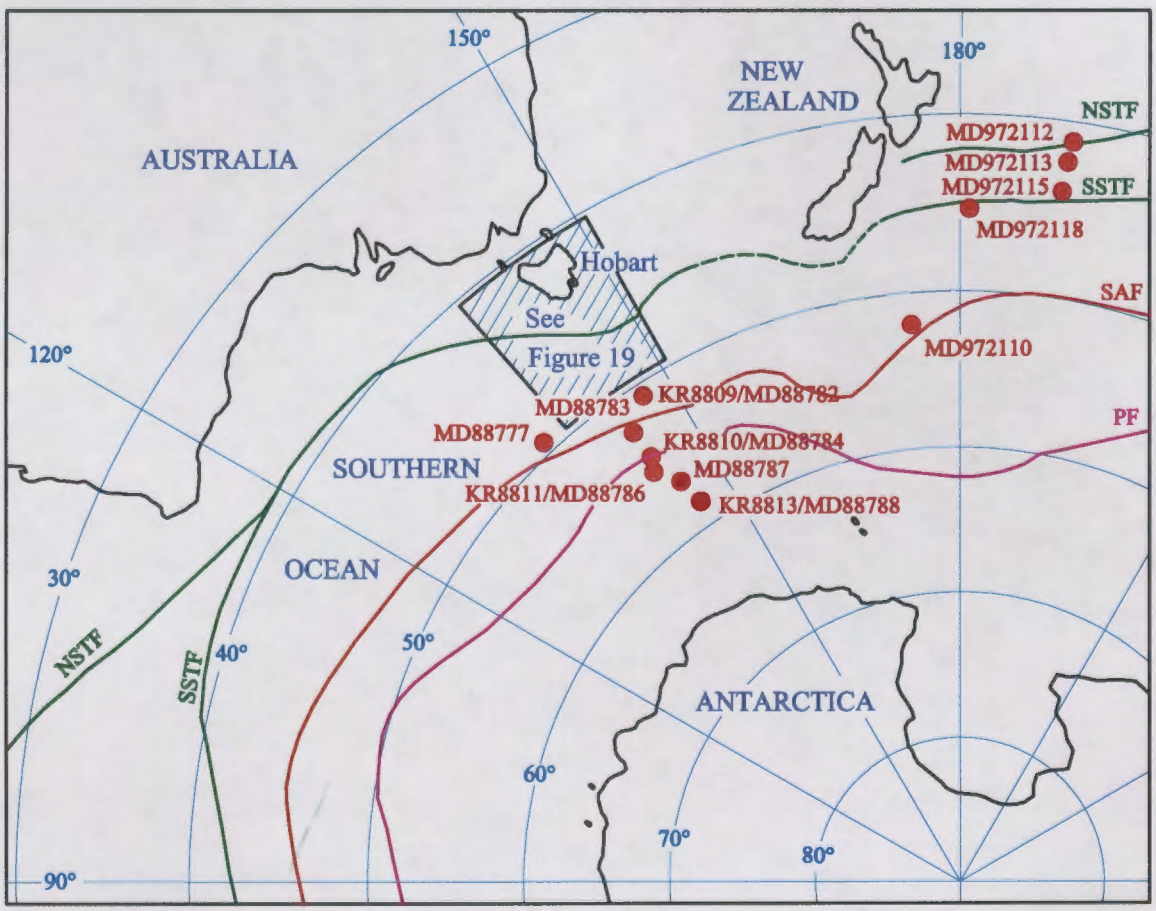


Fig. 28 Location of sediment samples from the study region in the Southern Ocean.

samples identified with a majority of *E. huxleyi*, a second count was made of subordinate species only (excluding *E. huxleyi* and gephyrocapsids) to determine the abundance and diversity of these species (Appendix A4). The second count ('subordinate species'), recorded percentages of individual species as percentages within the subordinate group (Table 12).

Main Components of the Surface Sediment Assemblage

Main Species	Environmental preference	Resistance to dissolution	Percentage of total assemblage
Emiliania huxleyi	tropical-polar		16.8 - 69.3%
'warm water' form		medium	
'cold water' form		low	
Gephyrocapsa muellerae	transitional	medium	10.4 -31.5%
Gephyrocapsa oceanica	tropical-transitional	medium	1.1 - 4.8%
Gephyrocapsa caribbeanica	tropical-transitional	medium	0.5 - 20.8%
small *Gephyrocapsa* spp	tropical-transitional	medium	2 - 20.8%
Subordinate Species			**Percentage within subordinate group**
Preferentially preserved			
Calcidiscus leptoporus	subtropical-transitional	high	43.6 - 83.1%
Helicosphaera carteri	tropical-transitional	high	6.2 - 24.1%
Coccolithus pelagicus	subantarctic	high	1.6 - 24.4%
Preferentially dissolved			
Syracosphaera pulchra	tropical-transitional	medium	0.8 - 12.1%
Umbilicosphaera sibogae	tropical-transitional	low	0.6 - 3.6%
Umbellosphaera tenuis	tropical-transitional	low	0.3 - 5.3%
Rhabdosphaera clavigera	tropical-transitional	low	0.3 - 2.2%
Oolithus fragilis	tropical-transitional	low	0.3 - 1.4%

Table 12 Main components of the Surface Sediment Assemblage. The assemblage is divided into 'Main Species', those counted first to establish the age of the sample, and the 'Subordinate Species' which is dominated by the three preferentially preserved species.

Variation in counting between the use of a light microscope and an electron microscope was identified. The light microscope results are considered to be more accurate based on the consistent pattern of calcite crystals under polarised light. Under the SEM there is some difficulty distinguishing the difference between dissolved forms of *E. huxleyi*, where the 'T' elements on the distal shield are absent (Plate 4; Fig. 1), and *G. muellerae* with a missing bridge (Plate 4; Fig. 2).

Dissolution

Changes to the sediment assemblage by dissolution have a direct effect on the reliability of biostratigraphic dating (based on calcareous nannoplankton) and it is important to recognise the degree of dissolution. For example, according to the solution index of Pujos (1985), the majority of surface sediments in this study have a solution index of 3 (Table 13), i.e., most coccoliths are moderately dissolved.

	Dissolution	Abundance of of intact coccoliths	Taxonomic Diversity	State of Solution-resistant structures	State of non-resistant structures
1	Few coccoliths slightly dissolved	~100%	Normal	Good	Good
2	Most coccoliths slightly dissolved	~70%	Normal	Good	Beginning of solution
3	Most coccoliths moderately dissolved	More than 40%	Few genera and/or spp absent	Some central structures missing	Strongly dissolved or missing
4	Most coccoliths strongly dissolved	~20%	Weak	Many central structures missing	
5	Very strong; almost non-calcareous sediment	No intact coccolith	Mono- or bi-specific		
6	Total dissolution; no calcareous sediment	Barren sediment			

Table 13 Nannofossil solution index (from Pujos, 1985).

B. Results

Of the 44 surface sediment samples examined, most contained abundant coccoliths as far south as the PF zone. Seven of the surface sediment samples had few or no coccoliths (Appendix A2). Two of these samples were collected at 50°S (between the STF and SAF) at a depth of 4350m. The remaining five samples were collected between 54°S to 57°S (south of

the PF), between the depths of 2880m and 3742m. These five samples were dominated by diatoms (Plate 4; Figs 3, 4).

Thirty samples had a dominance of *G. muellerae* over *E. huxleyi*, typically an indication of sediments older than 73 ka yr BP. The apparently older age of these coretops may be due to a combination of dissolution (reducing the number of *E. huxleyi*), erosion of younger sediments and reworking of older material. The remaining eight samples showed a majority of *E. huxleyi* over *G. muellerae*, i.e., are 73 ka or younger based on the biostratigraphic scheme of Thierstein et al. (1977). These samples (Appendix A4) are the focus of the following discussion.

Six of the eight samples are located south of Australia (Figs 19, 28), one to the north of the STF (GC07), two between the STF and SAF (MD 972108 and KR 8808), one between the SAF and PF (MD 88783) and two within the PF zone (KR 8810 and MD 88784). The remaining two samples are located east of New Zealand (Fig. 28), adjacent to the STF (MD972118) and between the SAF and PF (MD972110).

The assumption is made (unless otherwise stated) that the species have occupied the same environmental niche for the past 73 ka. The positions of the oceanic fronts are based on Belkin and Gordon (1996) and Rintoul et al. (1997), i.e., the STF between 46°S and 47°S south of Australia and 41°S and 45°S east of New Zealand; the SAF at approximately 52°S; the PF at ~54°S; and the Antarctic Divergence at ~63°S (as discussed in Chapter 4).

Assemblages

The components of the surface sediments include the 'main species' (*E. huxleyi* and *Gephyrocapsa* spp) and the 'subordinate species' (all other species) which can be divided into preferentially preserved and preferentially dissolved species (Table 12).

The assemblage identified in the surface sediments is dominated by *E. huxleyi* and *G. muellerae*, followed by *C. leptoporus*, *H. carteri* and *C. pelagicus* in descending order of abundance, and shows similarities to Assemblage B of the water column, a 'subtropical to transitional' assemblage, identified north of the STF. Assemblage B is dominated by *E. huxleyi* 'warm water' form with high abundances of *C. leptoporus* and *G. muellerae*. Differences between Assemblage B of the water column and the surface sediment assemblage include, *G. muellerae* as the second most dominant species in surface sediments compared to *U. tenuis* and *Syracosphaera* in the water column; and, the presence of *R. clavigera*, *U. sibogae*, *O. fragilis* and *C. pelagicus* in the surface sediments. The surface sediment assemblage shows little variation from north to south, with some minor changes across the STF, including a reduction of *C. leptoporus* and increases of *H. carteri* and *C. pelagicus* (Fig. 29).

Species

A total of nine modern taxa are preserved in surface sediments compared to 36 in overlying waters. Of the main species, *E. huxleyi* dominates, followed by *G. muellerae* (Table 12; Appendix A2). Within the subordinate species *C. leptoporus* is most abundant followed by *H. carteri* with *S. pulchra* the fourth most abundant species north of the STF (Fig. 29). *C. pelagicus* was present in low percentages (<4%) in all samples with the exception of KR 8808 with 24%. Reworked species including reticulofenestrids and *C. macintyrei* increased south of the SAF, i.e., south of 52°S.

Dissolution

Dissolution is identified by a reduction in diversity and abundance; poor preservation of fragile species dissolution of the resistant species, e.g., *Rhabdosphaera clavigera* (Plate 4; Fig. 6; McIntyre and McIntyre, 1971); coccoliths of *C. leptoporus* preserved as single shields; *G. muellerae*

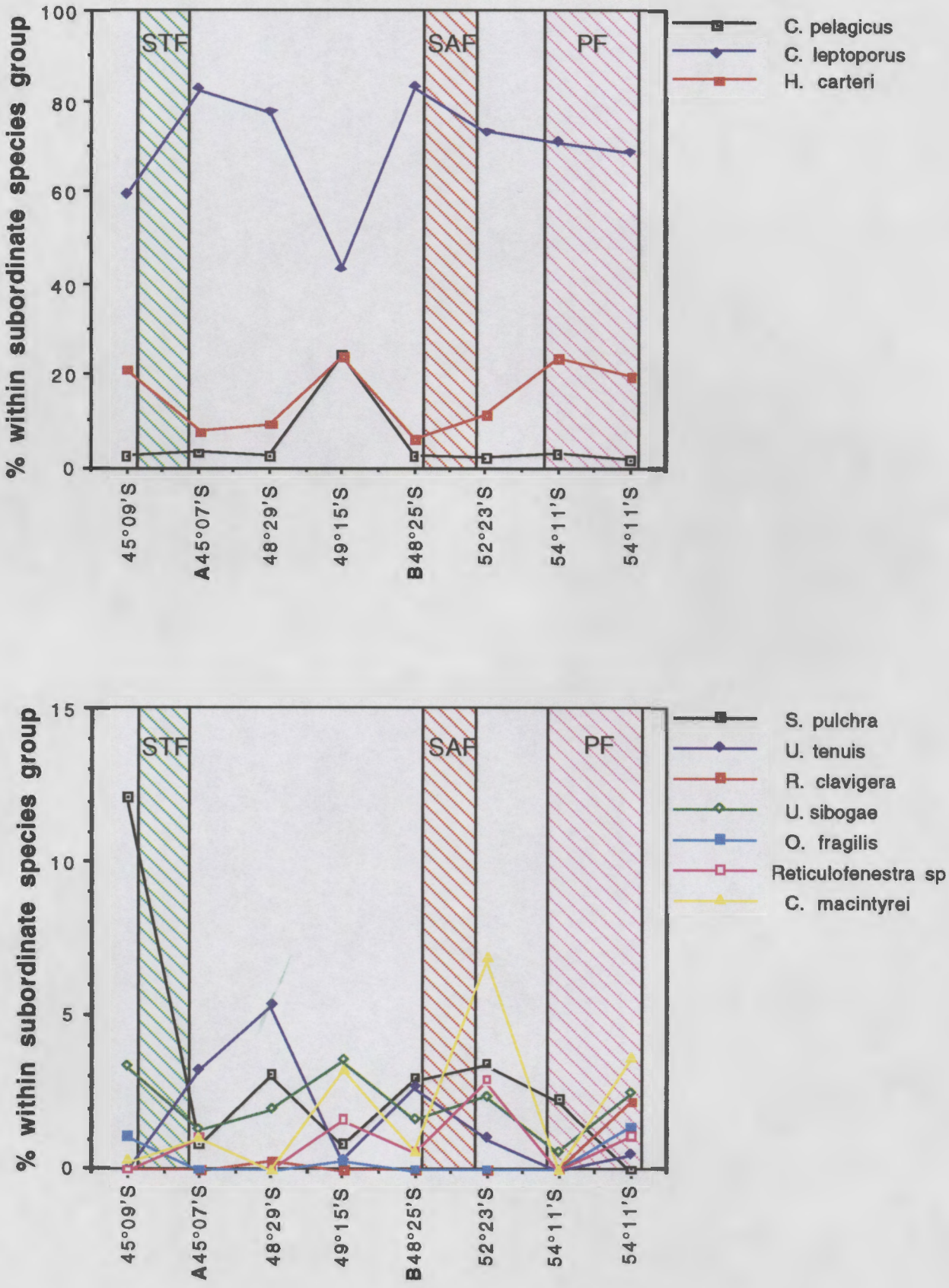


Fig. 29 Percentages of subordinate species in surface sediments dominated by *E. huxleyi*. Percentages reflect those within subordinate species group, excluding *E. huxleyi* and *Gephyrocapsa* spp. Stations prefixed by **A** are located east of New Zealand, and prefixed by **B** are southeast of New Zealand.

without a bridge (Plate 4; Fig. 2); and, reduced or missing 'T' elements on the distal shields of *E. huxleyi* (Plate 4; Figs 1, 5).

Coccoliths are present in two samples at 54°S (within the PF zone) at depths of 2785m and 2880m These samples show abundant diatoms with coccoliths strongly dissolved. South of the PF coccoliths were rare to absent at 2880m, suggesting that the southern extent of preservation of coccoliths in surface sediments lies between 54°S and 55°S in the Australian Sector of the Southern Ocean.

Reworking

The presence of older species, e.g., *Reticulofenestra* spp (Plate 5; Figs 6, 7, 8) and *Calcidiscus macintyrei* (Plate 5; Fig. 1), with a biostratigraphic range from Early Miocene to Early Pleistocene were found in small numbers (<4% of the subordinate species group) for most samples, with the highest percentage of 7% south of the SAF at 52°S.

C. Discussion

Assemblages

The surface sediment assemblage shows little variation from north to south with no apparent relationship to overlying water masses (unlike water column assemblages) except south of the STF. South of the STF, south of Australia, *C. pelagicus* and *H. carteri* increase with a decrease in *C. leptoporus*. Increases of *C. pelagicus* associated with the STF have been recorded previously in surface sediments adjacent to New Zealand and interpreted as phenomena of the STF (Burns, 1973). These changes may reflect increased productivity of *C. pelagicus* and *H. carteri* associated with changes in nutrients, or, are the result of preferential preservation of these species. As *C. leptoporus*, which is also preferential preserved, does not record a similar increase, the change is considered to reflect changes in nutrients. Similarly, increases of *H. carteri* in surface sediments of the

southwest Indian Ocean have been associated with high nutrient levels (Fincham and Winter, 1989). It is possible these species are useful as indicators of the paleo-latitude of the STF. However, as these species are preferentially preserved, their use as paleo-indicators should be approached with caution. In contrast, increases *H. carteri* at the PF are most likely the result of preferential preservation, as *H. carteri*, a subtropical species, would not be expected in high abundances in the PF zone. The increase of reworked species associated with the SAF is possibly associated with a reworking event at this location.

Previous studies have shown differences between surface sediment assemblages, living communities and overlying waters (McIntyre and Bé, 1967; McIntyre et al., 1990; Samtleben and Schröder, 1992; Knappertsbuch 1993); whereas others show similarities (Geitzenauer et al., 1976; Houghton, 1988; Eide, 1990). For example, species in surface sediments of the Norwegian-Greenland Sea change in abundance and diversity in association with overlying water masses (Samtleben and Bickert, 1990; Samtleben and Schröder, 1992; Samtleben et al., 1995b). The Norwegian-Greenland Sea has a well defined hydrographic regime, with warm, poleward-flowing water (Atlantic Current) to the east, and cold, equatorward-flowing water (East Greenland Current) to the west, separated by a strong frontal zone. In comparison, the Australian Sector of the Southern Ocean is influenced by one main east-flowing current (Antarctic Circumpolar Current) and the STF provides an effective barrier to warm, poleward-flowing currents. The two different hydrographic regimes between the northern and southern hemispheres limits comparative studies between the two regions.

The reduction in diversity from 36 species in the water column to nine in the underlying sediments is due in part to dissolution. Similarly, reduction in diversity between the living assemblages and sediment assemblages has been documented previously in the Pacific Ocean (McIntyre and Bé, 1967), and in the Norwegian-Greenland Sea (Samtleben and Schröder, 1992; Knappertsbusch, 1993; Samtleben et al., 1995a; 1995b).

The species composition of surface sediments in the Norwegian-Greenland Sea is similar to the surface sediments of this study.

The most noticeable feature of the surface sediment assemblage is the presence of subtropical species as far south as the PF zone, underlying subantarctic waters. The presence of subtropical species in this region may represent seasonal production (not reflected in the water column data), or the erosion of more recent sediments leaving an assemblage reflecting a warmer (than present) climatic interval. Similarly, subtropical to transitional species (*G. muellerae, H. carteri, S. pulchra* and *U. sibogae*) have been recorded in surface sediments underlying polar waters in the high latitudes of the North Atlantic, interpreted as advection via poleward-flowing, warm-water currents (Samtleben and Schröder, 1992).

The absence of poleward-flowing warm-water currents south of the STF excludes the same interpretation in this study, and it is suggested erosion of younger sediments has exposed an assemblage representing the warmer early Holocene interval. Erosion of sediments younger than 10 ka is common in this region (Wells and Connell, 1997), and the warmer early Holocene interval has been identified in sediments previously (McIntyre et al. 1970 and references therein; Baumann and Matthiessen, 1992).

The absence of calcareous nannoplankton in surface sediments south of 54°S, i.e., south of the present-day location of the PF zone, can be interpreted in two ways. Firstly, the PF zone may not have changed location from the early Holocene to present-day, where the subtropical zone extended as far south as 54°S, with an absence of the transitional zone during the early Holocene interval. It has been suggested the narrow niche of the transitional, or temperate, zone was absent during warming intervals, leaving the subtropical zone adjacent to the subantarctic zone (McIntyre et al., 1970).

Alternatively, the subtropical zone of the early Holocene (i.e., the surface sediment assemblage) may have extended south of 54°S during that interval with the PF zone located in a more poleward position than the present-day location. Subsequent cooling may have shifted the PF zone equatorward to its present-day position since the early Holocene interval, introducing colder, more corrosive waters south of 54°S. This would result in dissolution of coccoliths in the sediments and favour production of siliceous phytoplankton which would dilute any remaining coccoliths in surface sediments.

The first interpretation requires a poleward movement of approximately 7° to 8° latitude for the STF between the present-day location and the early Holocene with no change in location for the PF zone. Although this is possible, it is unlikely and the second interpretation is adopted here to explain the absence of calcareous nannoplankton in surface sediments south of 54°S, i.e., an equatorward movement of the PF between the early Holocene and present-day.

Seasonal production may account for the presence of species in the surface sediments of the PF zone which are absent from the overlying waters. However, it is difficult to understand highest production of subtropical species (e.g., *S. pulchra, H. carteri, U. tenuis, O. fragilis, R. clavigera* and *U. sibogae*) in subantarctic waters in seasons other than austral summer. The possibility of subtropical species being transported to high latitudes via warm-water eddies must also be considered.

Seasonal production, transport via warm-water eddies, dissolution and reworking may contribute to the species composition of the surface sediment assemblage. However, erosional exposure of older sediments is likely to be the main process forming the surface sediment assemblage.

Species

Gephyrocapsa muellerae

G. muellerae is a major component of all surface sediment samples down to the PF zone, with a reduction south of the SAF (Fig. 30). In comparison, the water column showed this species present north of 45°S with highest abundances north of the STF. Similarly, in the high latitudes of the Northern Hemisphere, *G. muellerae* is a major component of surface sediments underlying subpolar waters, although absent in overlying surface waters. This has been attributed to its preferential preservation and transportation via poleward-flowing, warm-water currents (Samtleben and Schröder, 1992; Samtleben et al., 1995b). The absence of similar currents (poleward-flowing, warm-water) south of the STF in the Southern Hemisphere precludes a similar explanation. It is possible short-term, warm water eddies transport subtropical species to high latitudes where they may represent a minor component of surface sediments.

High abundances of *G. muellerae* in surface sediments are interpreted as reflecting a subtropical to transitional depositional environment, rather than a tropical environment. North of the STF, surface sediments between 10°S and 45°S show highest abundances of *G. muellerae* in subtropical to transitional regions compared to low abundances in tropical regions (Hiramatsu and De Deckker, 1996), indicating this species preference for cooler waters. Discrepancies in abundances of *G. muellerae*, in this study, between the living assemblage in the subtropical to transitional region (Assemblage B with low abundance) and the surface sediment assemblage (high abundances), are attributed to preferential preservation and possible seasonal production, with highest production in seasons other than austral summer.

Calcidiscus leptoporus

C. leptoporus dominates the subordinate species (Table 12) in all surface sediment samples with lowest percentages south of the STF, south of

Australia and highest percentages in the New Zealand region, south of the STF (Fig. 29). Similarly, Burns (1973) documented an increase in this species south of the STF adjacent to New Zealand. *C. leptoporus* (along with *C. pelagicus* and *Gephyrocapsa* spp) is resistant to dissolution (McIntyre and McIntyre, 1971; Berger 1973a) and relative abundance of this species in sediments may reflect preferential preservation.

Some variation in size of *C. leptoporus* coccoliths was noted in surface sediments although uncommon. It is not possible to relate different sizes of coccoliths to separate morphotypes as suggested by previous authors (Hiramatsu and De Deckker, 1996; Knappertsbuch et al. 1997) as living coccospheres show variation of size on single coccospheres (Plate 2, Fig. 1).

Helicosphaera carteri

Within the subordinate species (Table 12), *H. carteri* (Plate 4, Fig. 7) recorded the highest percentages after *C. leptoporus* south of the STF and in association with the PF, south of Australia (Fig. 29). The lowest percentages were noted in the two samples east of New Zealand.

High percentages of *H. carteri* in surface sediments are unusual where this species is more often a lesser subordinate (McIntyre and McIntyre, 1971; Eide, 1990; Okada, 1992; Baumann and Matthiessen, 1992; Houghton, 1993; Hiramatsu and De Deckker, 1997a). The only other place this species is abundant in surface sediments is beneath the Benguela upwelling system (Giraudeau and Rogers, 1994). The peak of *H. carteri* south of the STF south of Australia, may be due to higher nutrient levels at this location, as previously suggested for increases of this species in surface sediments (Fincham and Winter, 1989; Giraudeau and Rogers, 1994). Alternatively, the peaks of *H. carteri* may be the result of preferential preservation. The peak corresponds to peaks of *C. pelagicus*, *C. macintyrei*, reticulofenestrids and *U. sibogae*, i.e., preferentially preserved species. *H. carteri* has been previously documented as resistant to dissolution (Berger, 1973a) which may also explain its higher abundance

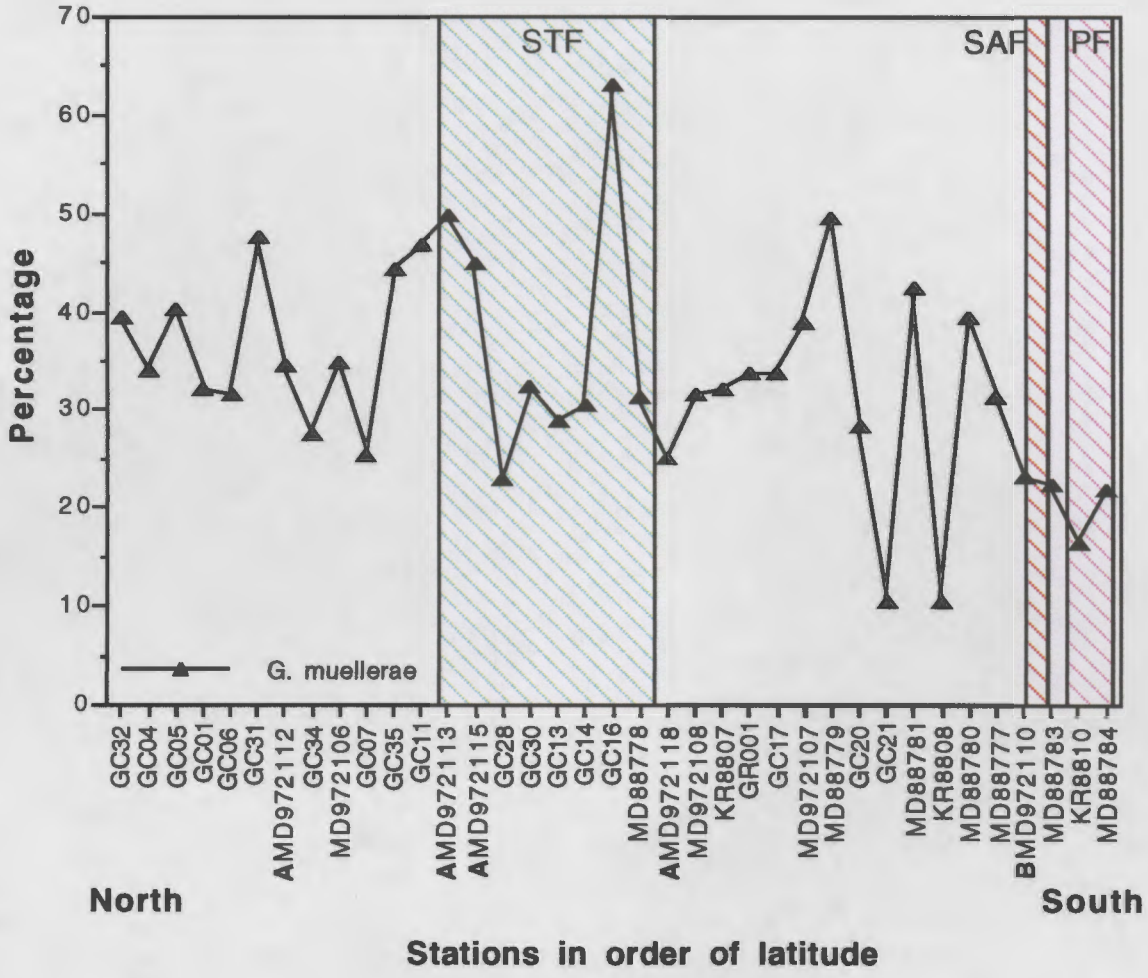


Fig. 30 Percentage of total assesmblage for *G. muellerae*. Stations prefixed by **A** are located east of New Zealand, and prefixed by **B** are southeast of New Zealand.

in subantarctic sediments compared to its subtropical to transitional distribution in the water column.

Coccolithus pelagicus

The low overall percentages of *C. pelagicus* in surface sediments of this region would appear to be unusual considering this species preference for colder waters and its resistance to dissolution, particularly when compared to surface sediments in the high latitudes of the Northern Hemisphere. The explanation put forward by McIntyre and Bé (1967), that *C. leptoporus* has taken over the niche recently left vacant by *C. pelagicus* in the Southern Hemisphere (see Chapter Four), is considered to explain its low abundance in surface sediments of this region. *C. pelagicus* is known to occupy a temperate region between subtropical and subpolar regions in the Northern Hemisphere, a narrow niche which may have disappeared in the post glacial warming at 8 ka with the poleward movement of subtropical waters (McIntyre et al., 1970).

The peak in *C. pelagicus* south of the STF, south of Australia, corresponds to a minor peak of reworked species and a decrease in *C. leptoporus* (Fig. 29) and may be the result of preferential sorting. Previous results from the subantarctic found *C. pelagicus* absent in most coretops, and where present, was interpreted as loss of coretops and reworking (Geitzenauer, 1972). In the New Zealand region peaks of *C. pelagicus* have been interpreted as a phenomena of the STF resulting from localised currents which have preferentially sorted the larger coccoliths (Burns, 1973). In contrast, sample MD 88783 south of the SAF (52°S) registered a higher percentage of reworked species with no corresponding increase of *C. pelagicus* (Fig. 29), suggesting increases in *C. pelagicus* are not always explained by reworking and may reflect increased production related to environmental factors (e.g., increased nutrients).

Syracosphaera pulchra

S. pulchra is the only member of this genus represented in the surface sediments (Plate 3; Fig. 2). Similarly, *S. pulchra* was the only

Syracosphaera sp. found in surface sediments of the southwest Indian Ocean (Fincham and Winter, 1989). This species was identified in all surface sediment samples (i.e., younger than 73 ka) with the exception of the most poleward sample (MD 88784), with the highest percentage (12%) recorded north of the STF, confirming this species preference for warmer waters (Burns, 1973; Geitzenauer et al., 1976; Samtleben et al., 1995a). *S. pulchra* has been identified as a consistent component of surface sediments in previous studies (McIntyre and McIntyre, 1971; Eide, 1990; Baumann and Matthiessen, 1992), particularly in the Norwegian Sea where it is interpreted as transported via poleward-flowing, warm-water currents (Samtleben et al., 1995b).

Umbilicosphaera sibogae

U. sibogae was found in all surface sediment samples (Fig. 29) including those within the PF zone, with highest percentages south of the STF, south of Australia. This species has been identified previously as preferring subtropical environments (McIntyre and Bé, 1967). The presence of this species within the PF zone confirms its resistance to dissolution, previously noted (McIntyre and McIntyre, 1971), rather than susceptible to dissolution (Roth and Coulbourn, 1982). *U. sibogae* has been reported as a lesser component of surface sediments (McIntyre and Bé, 1967; Burns, 1973; Okada, 1992; Samtleben and Schröder, 1992; Giraudeau and Rogers, 1994; Hiramatsu and De Deckker, 1997a). In the southwest Indian Ocean north of 38°S, *U. sibogae* is the fourth most dominant species in surface sediments (Fincham and Winter, 1989).

Umbellosphaera tenuis, Rhabdosphaera clavigera* and *Oolithus fragilis

These three species were identified as far south as the PF zone, where *U. tenuis* showed the highest percentages (<5.36) followed by *O. fragilis* (<1.38%) and *R. clavigera* (<2.2%). These three species have been previously described as warm-water species (McIntyre and Be, 1967) less resistant to dissolution (Roth, 1994), particularly *O. fragilis*. It is possible the established dissolution ranking of these species is in doubt as *R. clavigera* has been recorded in surface sediments at 55°S, south of New

Zealand (Burns, 1973), and *O. fragilis* and *U. sibogae* are relatively common in heavily dissolved samples of Quaternary cores collected in the southeast Indonesian Basin (Biekart, 1989).

Dissolution

The ^{14}C date for core GC04 (discussed in Chapter Six) recorded a Holocene age between 5cm and 8cm with *G. muellerae* in slightly higher numbers than *E. huxleyi*, suggesting preferential dissolution of *E. huxleyi*. In contrast, the presence of *U. sibogae*, *O. fragilis*, *R. clavigera* and *U. tenuis*, susceptible to dissolution, indicates dissolution is not severe, and factors other than dissolution may account for the reduction of *E. huxleyi* in surface sediments. Erosion of younger sediments and reworking are considered to be the main factors influencing the abundance patterns of species in surface sediments of his region.

It is difficult to distinguish the 'cold water' and 'warm water' morphotypes of *E. huxleyi* in the surface sediments and comparisons of abundances between the two in surface sediments cannot be used as a proxy for the location of overlying hydrographic fronts and associated water masses, as has been previously suggested (Hiramatsu and De Deckker, 1996). The majority of *E. huxleyi* coccoliths in the sediments appear to be dissolved forms of a heavily calcified type, often with no central area structure and reduced 'T' elements (Plate 4; Fig. 5). These coccoliths are most like the 'warm water' morphotypes, suggesting the more fragile 'cold water' morphotypes are rare or absent in sediment samples.

It is sometimes difficult to distinguish between dissolved forms of *G. muellerae* (without a bridge) and *E. huxleyi* (with no 'T' elements) in surface sediments. The dissolution pattern of these two species and the difficulty distinguishing between the two in sediments has been noted previously (McIntyre and McIntyre, 1971). *G. muellerae* without bridges is attributed in this study to dissolution. Although, Okada (1992)

attributed *G. oceanica* without bridges in surface sediments of marginal seas along the coast of Japan to malformation related to nutrient deficiency (Okada, 1992). Bridgeless *G. muellerae* occur in all samples from north of the STF to the PF region independent of nutrient levels.

Single shields of *C. leptoporus* coccoliths are common in the surface sediments indicating dissolution. The first effects of dissolution break the central tube between the two shields of the coccolith (McInytre and McIntyre, 1971) and the ratio between single shields and complete coccoliths has been used in past studies as an index for dissolution (Matsuoka, 1990).

It is evident the surface sediment assemblage in this region has been subjected to the effects of dissolution although the effect is not considered to be severe.

The preservation of calcareous organisms (including coccoliths) in surface sediments can be used to indicate the depth of the lysocline. North of the SAF coccoliths are abundant in surface sediment samples at a water depth of 4452m (46°S) and at 4132m (49°S) indicating the calcite lysocline is below these depths at these locations. South of the SAF (50°S) coccoliths are rare in surface sediment samples at a depth of 4350m, indicating the lysocline is above this depth at this latitude. Similarly, the study of coccoliths in surface sediments in the region of New Zealand, found coccoliths rare or absent at depths below 4000m (Burns, 1973). Within the PF zone (54°S) coccoliths are present at a depth of 2800m, although strongly dissolved, suggesting the calcite lysocline is close to this depth at this latitude. South of the PF, coccoliths are rare or absent in surface sediments at a depth of 3742m, where diatoms are abundant. Previous research estimates the calcite saturation horizon at 3400m in the Southern Ocean (Takahashi et al., 1981), and the calcite lysocline on the southeast Indian Ridge at about 4300m (Howard and Prell, 1994).

Erosion and Reworking

The low number of surface sediment samples dominated by *E. huxleyi* (eight of 45 samples) is attributed mainly to the effects of erosion of younger sediments, coupled with reworking and dissolution in the region. Previous studies have documented erosion and reworking in the same region (Wells and Okada, 1996) with erosion of sediments younger than 10 ka described as common (Wells and Connell, 1997) and 33 coretops in the broader region identified with an age of Late Pleistocene (Osborn et al., 1983; Belford, 1989).

The presence of extinct taxa indicates the region has been subject to reworking where older material has been introduced via slumping from adjacent outcrops, or, erosion and transportation via bottom currents. Reworked species of calcareous nannoplankton are common in most sediment samples and in low abundances are not considered to effect the biostratigraphic age.

D. Summary

The surface sediment assemblage reflects a subtropical to transitional environment and shares similarities with Assemblage B of the water column. The assemblage shows little variation from north of the STF to the PF zone with the exception of some minor variations south of the STF, south of Australia. The increases south of the STF are interpreted as reflecting changes in nutrients at this location. Increases associated with the SAF (reworked species) and the PF (*H. carteri*) are considered to be the result of preferential preservation through dissolution and reworking. The poleward extent of calcareous nannoplankton preserved in surface sediments lies between 54°S and 55°S.

Three control factors are identified associated with the preservation of calcareous nannoplankton in surface sediments of this region. Firstly, the environment of the overlying surface and subsurface waters, i.e.,

subtropical to transitional waters control the species composition of the initial assemblage that will in part be preserved in the sediments. The presence of a subtropical species underlying subantarctic waters in the PF zone is interpreted as reflecting the warmer early Holocene interval, where subtropical surface waters may have reached as far south as the present-day PF zone. Seasonal production of some species may also contribute to the differences between the living assemblages and the surface sediment assemblage.

Secondly, dissolution is identified as a contributing factor in the preservation of sediments in this region. Dissolution is depth dependent, where calcareous sediments below the lysocline are poorly preserved and below the CCD are absent. Dissolution is identified in all sediment samples by overall reduced abundance and diversity, coupled with poor preservation of individual coccolilths. Preferential preservation contributes to higher abundances of *G. muellerae*, *H. carteri* and *C. leptoporus* in the surface sediments. Surface sediments in the PF zone reflect an increase in dissolution (low abundance and greater dissolution of coccoliths) indicating more corrosive waters at this location, possibly related to the Circumpolar Deep Water which upwells south of this front (Fig. 6).

Thirdly, erosion and associated reworking will determine the geographic distribution of species in surface sediments. The results of this study indicate erosion of younger sediments has occurred, leaving an assemblage that reflects the warmer early Holocene interval. The presence of extinct reworked species in small percentages indicates minor reworking of older material during this early Holocene interval. Increases in more robust, preferentially preserved species associated with the SAF and PF, may reflect reworking at these locations.

Chapter Six Down-core sediments

A. Introduction

B. Results

1. Low resolution study of cores from the South Tasman Rise
2. High resolution study of GC07 from the South Tasman Rise
   a) Stratigraphy
   b) Calcareous nannoplankton

C. Discussion

1. Low resolution study of cores from the South Tasman Rise
   a) Stratigraphy
   b) Reworking and dissolution
2. High resolution study of GC07 from the South Tasman Rise
   a) Dissolution
   b) Reworking
   c) Stratigraphy
   d) Paleoceanography
   e) Species

D. Summary

1. Stratigraphy
2. Paleoceanography
   a) Species
   b) Oxygen isotope stages

A. Introduction

The study of deep-sea sediments is instrumental in understanding past climatic processes in the oceans and atmosphere. Variables used as paleoclimate proxies include oxygen isotopes, microfossil assemblages, and percentages of biogenic components such as calcium carbonate. It is important to provide a sound stratigraphic framework for such studies. This study uses the biostratigraphy of calcareous nannoplankton based on Okada and Bukry (1980) and Thierstein et al. (1977), supplemented by acme zones (Weaver and Thomson, 1993; Weaver, 1993; Jordan et al. 1996, Beaufort and Giraudeau, unpub.) to provide a stratigraphic framework for a paleoceanographic study of the South Tasman Rise.

The focus of this section of the study is changes in assemblages of calcareous nannoplankton and the interpretation of those changes in terms of paleoceanographic conditions, i.e., the movement of oceanic fronts, the distribution of surface water masses, and the pattern of sea-surface temperature (SST) through time. The first objective is to identify a core from the South Tasman Rise with a Holocene coretop, a reasonable sedimentation rate and little downcore disturbance if possible. Core GC07 met the above criteria and was sampled at regular intervals to establish the biostratigraphy based on calcareous nannoplankton datum events, supplemented by ^{14}C dates, $\delta^{18}O$ data and $\%CaCO_3$ data.

Downcore samples from six additional cores (GC04, GC20, GC31, GC32, GC34 and GC35) were examined for calcareous nannoplankton species. The percentages of calcareous nannoplankton in these cores reflect percentages of the total calcareous nannoplankton assemblage. Percentages in GC07 for *E. huxleyi* and *Gephyrocapsa* spp are percentages of the total assemblage and percentages for the remaining subordinates species are percentages of the subordinate species group only (i.e., excluding *E. huxleyi* and *Gephyrocapsa* spp.) It should be noted that low percentages for some of the subordinate species (*O. fragilis, R. clavigera, U. sibogae* and *U. tenuis*) and the reworked species (*Reticulofenestra* spp,

Cyclicargolithus floridanus, *C. macintyrei* and *P. lacunosa*) are too low to provide a reliable basis for the interpretation of paleoclimatic conditions. However, combined with other data in this study and previous studies in the region (Wells and Okada, 1996), they provide supporting information.

Florisphaera profunda was noted in GC07, though extremely rare, and is usually found at lower latitudes. It is not included in the results of this study, other than to note here its occasional presence. Hiramatsu and De Deckker (1997a) found *F. profunda* in low abundances in a Quaternary core east of Tasmania at 44°S. This study (Chapter 4) identified a warm tropical to subtropical assemblage in waters east of Tasmania at 43°S where the presence of *F. profunda* in sediments would be expected.

The interpretation of calcareous nannoplankton assemblages in sediments in terms of paleotemperature should be approached with caution, particularly in this region. As Berger (1973b) points out, the assemblages preserved in sediments are altered due to species' differential resistance to dissolution (Berger, 1973b). Berger (1973b) suggests the term 'taphotemperatures' rather than paleotemperatures based on the presence/absence of warm-water and cold-water species in those assemblages.

B. Results

Eighteen deep-sea gravity cores were collected from the South Tasman Rise (Fig 24) in the Australian Sector of the Southern Ocean, 1995, for a total of 83 samples (Table 1). Initial biostratigraphic analysis of coretops based on calcareous nannoplankton show the top of GC07 had a majority of *E. huxleyi* (Plate 1, Figs 1, 2, 3, 4; Plate 4, Figs 1, 5) over *G. muellerae* (Plate 5; Fig. 2) indicating an age of 73 ka or younger (Thierstein et al., 1977). ^{14}C dating established a coretop of Holocene age and this core was chosen for the paleoclimatic study. The remaining six cores (GC04, GC20, GC31, GC32, GC34 and GC35) were sampled at low resolution (Appendix A3) to determine the extent of the Quaternary sediments in the region,

the presence or absence of hiatuses and to estimate the extent of erosion in coretop sediments. Biostratigraphic information from these samples supplement the study of core GC07. The bottom of all cores were sampled for calcareous nannoplankton by Shafik (Exon et al., 1996) who determined a Late Quaternary age (<450 ka) for the base of all seven cores based on the absence of *P. lacunosa.* The results of this study are in agreement with these findings although, *P. lacunosa* (Plate 5; Fig. 3) was identified in low numbers at the base of GC07, attributed to reworking.

Low-resolution analysis of six cores from the South Tasman Rise

Six cores (GC04, GC20, GC31, GC32, GC34 and GC35) show *G. muellerae* dominant over *E. huxleyi* in the coretops (Fig. 31). GC04 had a marginally higher percentage of *G. muellerae* (23.5%) over *E. huxleyi* (21.7%) with a radiocarbon date of 3,160 yr BP (Samson, 1998) between 5cm to 8cm. The percentage of *G. muellerae* increases to 52% at 50cm and 71% at 249cm with a corresponding reduction in *E. huxleyi. G. caribbeanica* showed 4.5% at 50cm. Small *Gephyrocapsa* spp (Plate 5; Fig. 4) are rare or absent and the abundance variations between *C. leptoporus* and *C. pelagicus* showed the opposite pattern.

The coretop of GC20 showed 71% of *G. muellerae* and 7% of *E. huxleyi* with *G. caribbeanica* and small *Gephyrocapsa* spp absent. No radiocarbon dates were carried out for GC20, GC31, GC32, GC34 or GC35. The coretop for GC31 shows 26% for *G. muellerae* and 18% for *E. huxleyi* with small percentages for *G. caribbeanica* at 75cm and no small *Gephyrocapsa* spp. At the depth of 75cm there is a noticeable increase of reworked species including *C. macintyrei, Discoaster* sp. (Plate 5; Fig. 5), *Reticulofenestra* spp and *P. lacunosa,* coupled with a reduction for all other species (excluding *G. muellerae*). The coretops for GC32, GC34 and GC35 show a majority of *G. muellerae* over *E. huxleyi* with the greatest margin recorded for GC35 with 46% *G. muellerae* and 2% *E. huxleyi.* The abundance variations between *C. leptoporus* and *G. muellerae* show a mirror image for these three cores. Highest percentages for *G.*

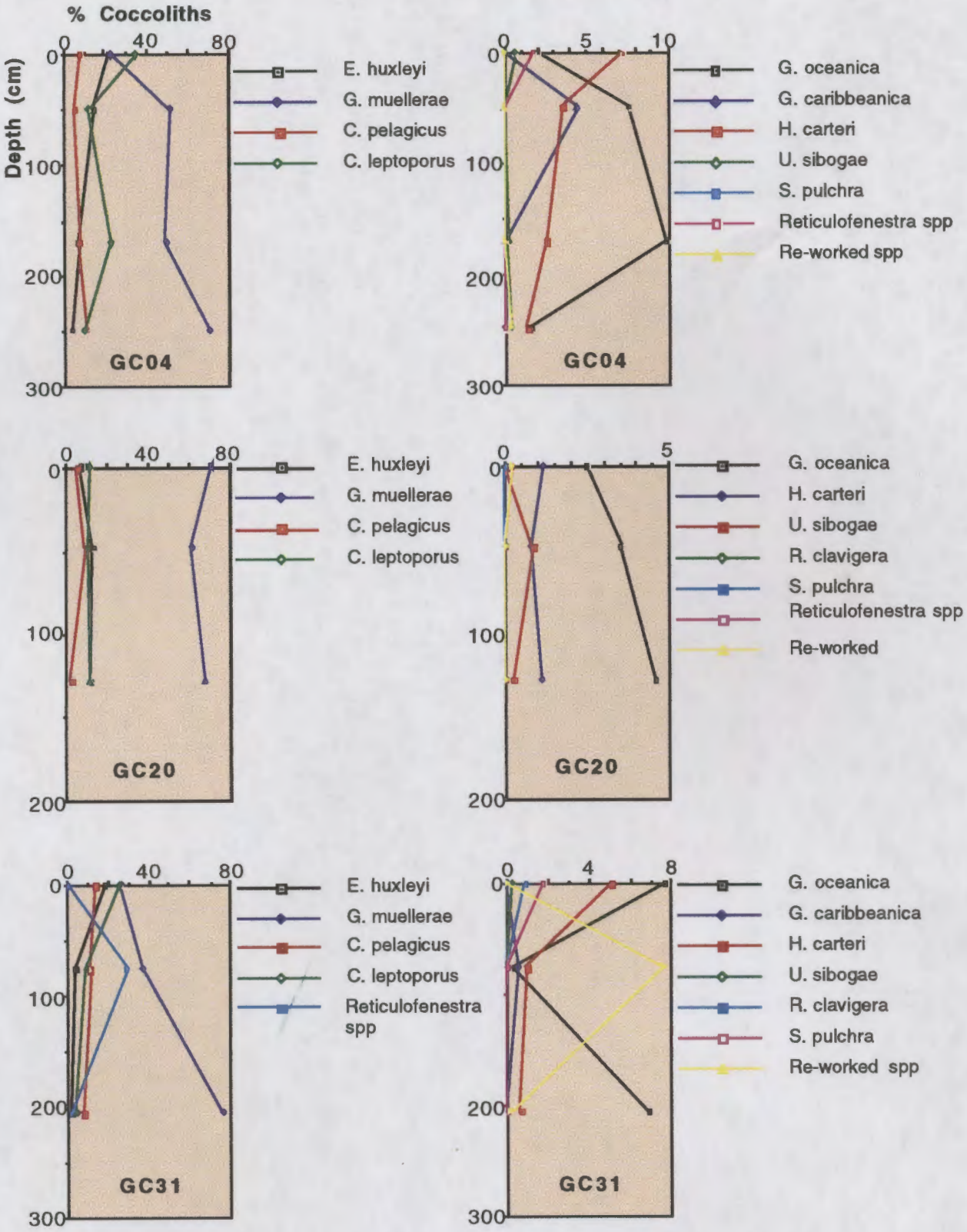


Fig. 31a Relative abundance of calcareous nannoplankton in cores GC04, GC20, GC31.

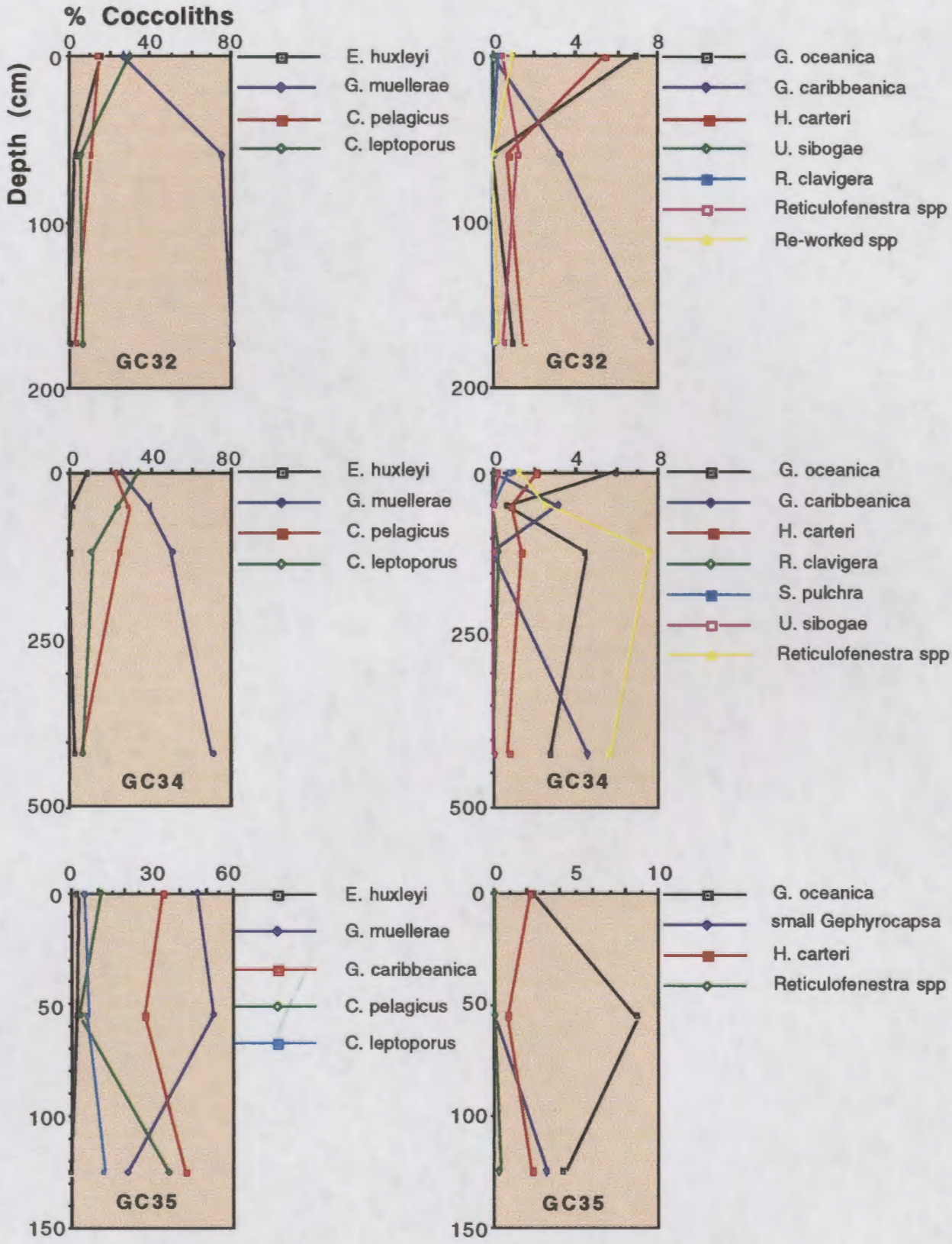


Fig. 31b Relative abundance of calcareous nannoplankton in cores GC32, GC34 and GC35.

caribbeanica were recorded at 34% in the coretop of GC35. The coretops of these cores indicate an age greater than 73 ka (Thierstein et al., 1977) and the variation in abundances of species downcore supplements the information for core GC07, e.g., the absence of small *Gephyrocapsa* spp, increases of reworked species indicating core disturbance and the negative covariance between *C. leptoporus* and *G. muellerae*.

High resolution study of core GC07 from the South Tasman Rise.

Core GC07, is located adjacent to the STF at a latitude of 45°S (Fig. 28). The top two meters of this core were sampled at 10cm intervals and the remainder (210cm to 510cm) sampled at 20cm intervals (Appendix A1). One coccolith barren interval was identified between 120cm and 123cm. Preservation of calcareous nannoplankton is affected by dissolution, similar to the surface samples described in the previous chapter.

Stratigraphy

Five oxygen isotope stages, stages 1 to 5, have been identified in core GC07 based on biostratigraphy of calcareous nannoplankton combined with $\%CaCO_3$ data (McCorkle, unpub.), supplemented by $\delta^{18}O$ data and ^{14}C dates (Samson, 1998) for the upper 150cm (Fig 32). The ages of these stages follow those given by Martinson et al. (1987) shown in Figure 14 of Chapter 2. Stage 1 is identified between 0cm to 70cm; stage 2 between 70m and 110cm; stage 3 between 130cm and 250cm; stage 4 between 290cm and 370cm; and, stage 5 from 390cm to the base of the core.

E. huxleyi is identified in all samples placing the bottom of core GC07 above the FO of this species, i.e., late stage 8 (Thierstein et al., 1977) or the boundary of stages 7 and 8 (Weaver and Thomson, 1993). The dominance reversal between *E. huxleyi* and *G. muellerae* occurs at 40cm suggesting an age of 73 ka for this depth (Thierstein et al., 1977), a date which is not in agreement with ^{14}C dates for core GC07. The domination of all samples by *G. muellerae* below 40cm indicates an age between stages 4 and 7, following Weaver and Thomson (1993). The presence of *P. lacunosa* in

GC07 is interpreted as a result of reworking with no stratigraphic importance; the last occurrence (LO) of *P. lacunosa* is usually found in mid-stage 12 (Thierstein et al., 1977).

The $\%CaCO_3$ shows higher values between 0cm to 70cm, with low readings between 70cm and 110cm followed by higher percentages between 110cm and 270cm. The percentage decreases at a depth of 290cm followed by an overall increase for the remainder of the core (McCorkle, upub.). The ^{14}C dates for GC07 (Samson, 1998) are as follows:

0-3cm	1167 yr BP
48-49cm	11020 yr BP
57-58cm	11420 yr BP
80-83cm	14880 yr BP

The $\delta^{18}O$ curve records values lower than 1.5‰ between 0cm and 40cm with alternating increases and decrease between 45cm and 70cm, followed by higher values of 2.5‰ to 3.5‰ for the depths of 70cm to 150cm (Samson, 1998). The absence of $\delta^{18}O$ data below 150cm leaves the interpretation of stages 4 and 5 as tentative only.

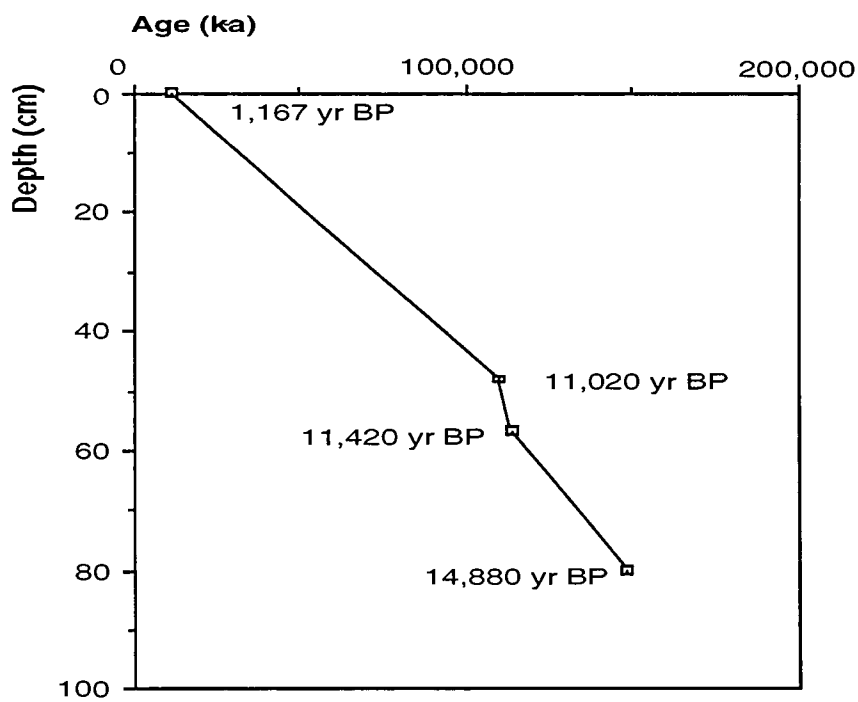


Fig. 33 Radiocarbon dates for GC07 (adapted from Samson, 1998).

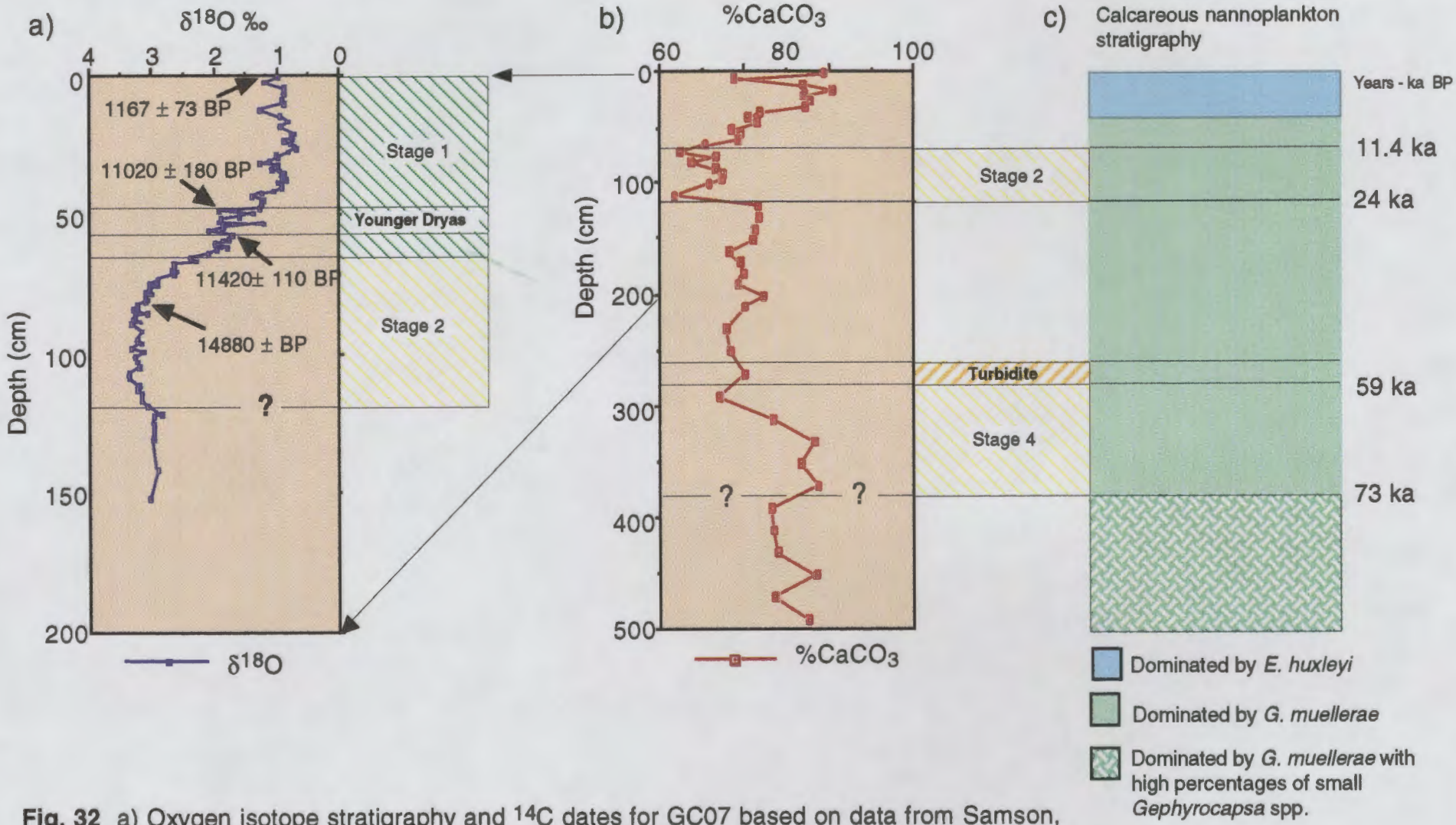


Fig. 32 a) Oxygen isotope stratigraphy and ^{14}C dates for GC07 based on data from Samson, 1998; b) $\%CaCO_3$ for GC07 based on data from McCorkle (unpub.); c) Calcareous nannoplankton stratigraphic datum events. Dates of oxygen isotope stages follow Martinson et al., 1987.

The sedimentation rate for GC07 between the depths of 0cm and 80cm recorded an increase in sedimentation between approximately 45cm and 60cm (Fig. 33).

Calcareous nannoplankton

Oxygen Isotope Stage 1. Stage 1, between 70cm and 0cm, showed higher percentages of subtropical species (*U. sibogae, R. clavigera, G. oceanica, U. tenuis, S. pulchra* and *H. carteri*) relative to subantarctic species (*C. pelagicus* and *G. muellerae*). Highest percentages for *C. leptoporus* and lowest percentages for *C. pelagicus* (Fig. 34) were found in this interval with *C. leptoporus* dominant over *C. pelagicus*. The increase in sedimentation rate between 60cm and 45cm is associated with changes in the assemblage including the presence of *C. macintyrei* and *C. floridanus* (Fig. 35; Appendix A1). The reversal in dominance between *E. huxleyi* and *G. muellerae* occurs at 40cm. Between the depths of 40cm and 0cm the *Emiliania huxleyi* acme zone is recognised, i.e., *E. huxleyi* dominates the sediments (Fig. 34).

Oxygen Isotope Stage 2. Stage 2, between the depths of 120cm and 70cm, shows higher percentages for *C. pelagicus* and *G. muellerae* where *C. pelagicus* dominates over *C. leptoporus* coupled with a reduction of subtropical species and *E. huxleyi* (Fig. 34). A barren zone in early stage 2 was identified at 120cm with a minor increase of reworked species (*Reticulofenestra* sp. and *H. sellii*) at 110cm.

Oxygen Isotope Stage 3. Stage 3 is recognised between 250cm and 120cm by decreases in *C. pelagicus* and increase in *C. leptoporus* compared to stage 4 although *C. pelagicus* remains dominant over *C. leptoporus* with an exception found at 130cm (Fig. 34). Increases of subtropical species occur between 250 and 130cm. Highest percentages of *G. oceanica* and *G. caribbeanica* are found in this interval. Percentages of *G. muellerae* are higher in early stage 3 (250cm) with a decrease in abundance through to late stage 3.

Turbidite. At the depth of 270cm increases in reworked species including *Reticulofenestra* spp, *C. floridanus, Discoaster* spp and *C. macintyrei* are noted (Fig. 36). A reduction for most other species is found at this interval where the core-log clearly shows a turbidite structure.

Oxygen Isotope Stage 4. Between the depths of 370cm and 290cm increases in subantarctic species and decreases in subtropical to transitional species are found in comparison to stage 5 (Fig. 34). A minor peak of reworked species (*Reticulofenestra pseudoumbilica, R. gelida, C. macintyrei, C. floridanus, Discoaster* sp., *Sphenolithus* sp. and small reticulofenestrids) is found at 370cm with a peak of small *Gephyrocapsa* spp at 310cm. One coccolith of *P. lacunosa* was identified at 330cm.

Oxygen Isotope Stage 5. Stage 5 is identified between 510cm and 390cm by high percentages (up to 34.5% of the total assemblage) of small *Gephyrocapsa* spp which show an oscillating pattern for this interval and a negative covariance with *G. muellerae* (Fig. 34). Subtropical species are more abundant in this interval compared to stage 4. *C. leptoporus* dominates over *C. pelagicus* in early stage 5 (510cm) with a reversal in dominance between 490cm and 410cm with *C. leptoporus* dominating again in late stage 5 (390cm). Reworked species are more abundant in early stage 5.

C. Discussion

Low resolution analysis of six cores from the South Tasman Rise

Interpretation of the additional six cores (GC04, GC20, GC31, GC32, GC34 and GC35) remains tentative based on the few samples available and is provided as additional supporting environmental and stratigraphic information for the interpretation of GC07.

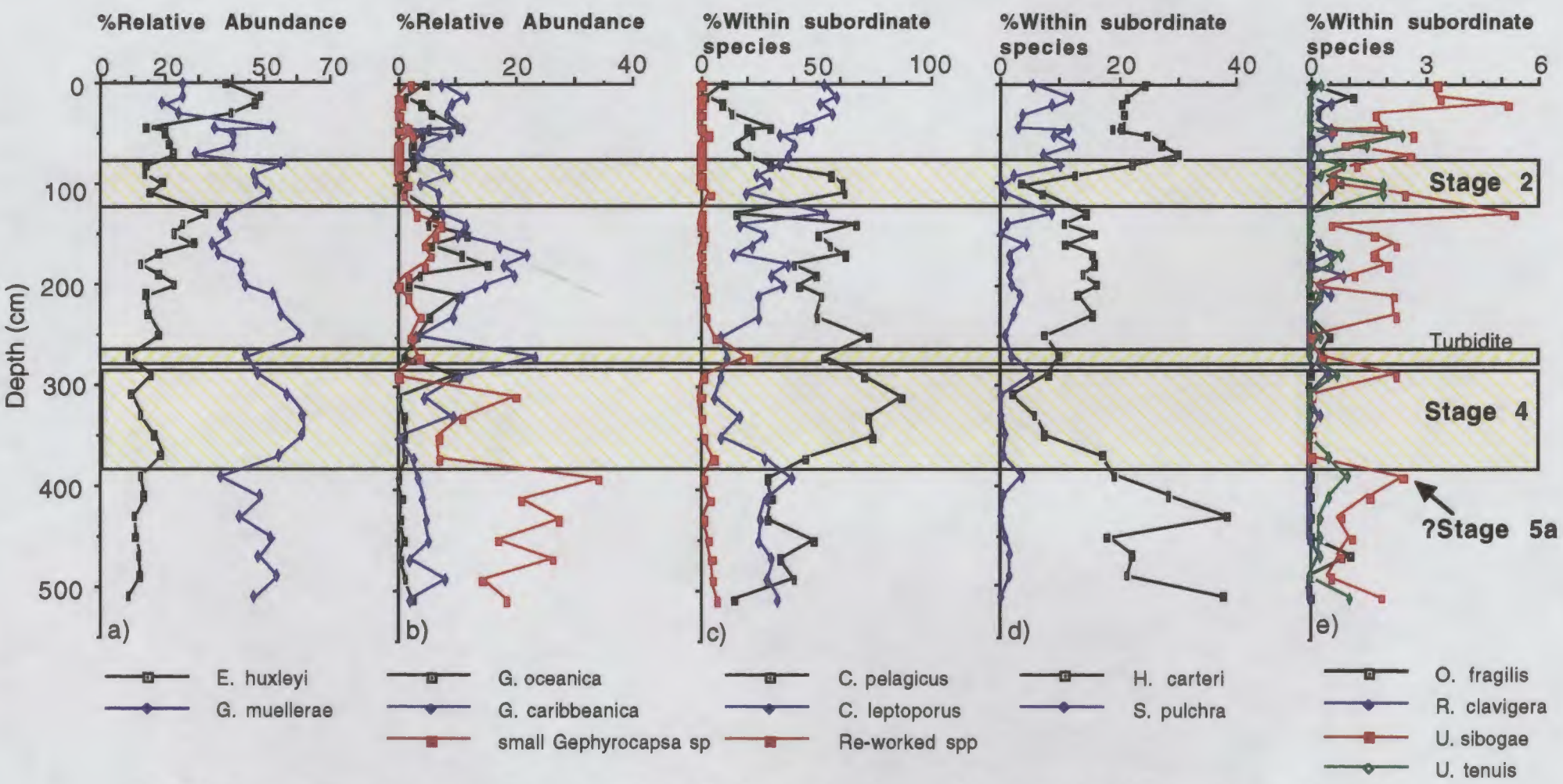


Fig. 34 Percentages of species for core GC07. a) Relative abundance of *E. huxleyi* and *G. muellerae*; b) relative abundance for subtropical to transitional *Gephyrocapsa* spp; c) percentage within subordinate species group for *C. pelagicus*, *C. leptoporus* and re-worked species(includes *C. macintyrei*, *C. floridanus* and *Discoaster* sp.); d) percentage within subordinate species group for preferentially preserved subtropical to transitional species; e) percentage within preferentially dissolved subtropical to transitional species. Subordinate species group - all species excluding *E. huxleyi* and *Gephyrocapsa* spp.

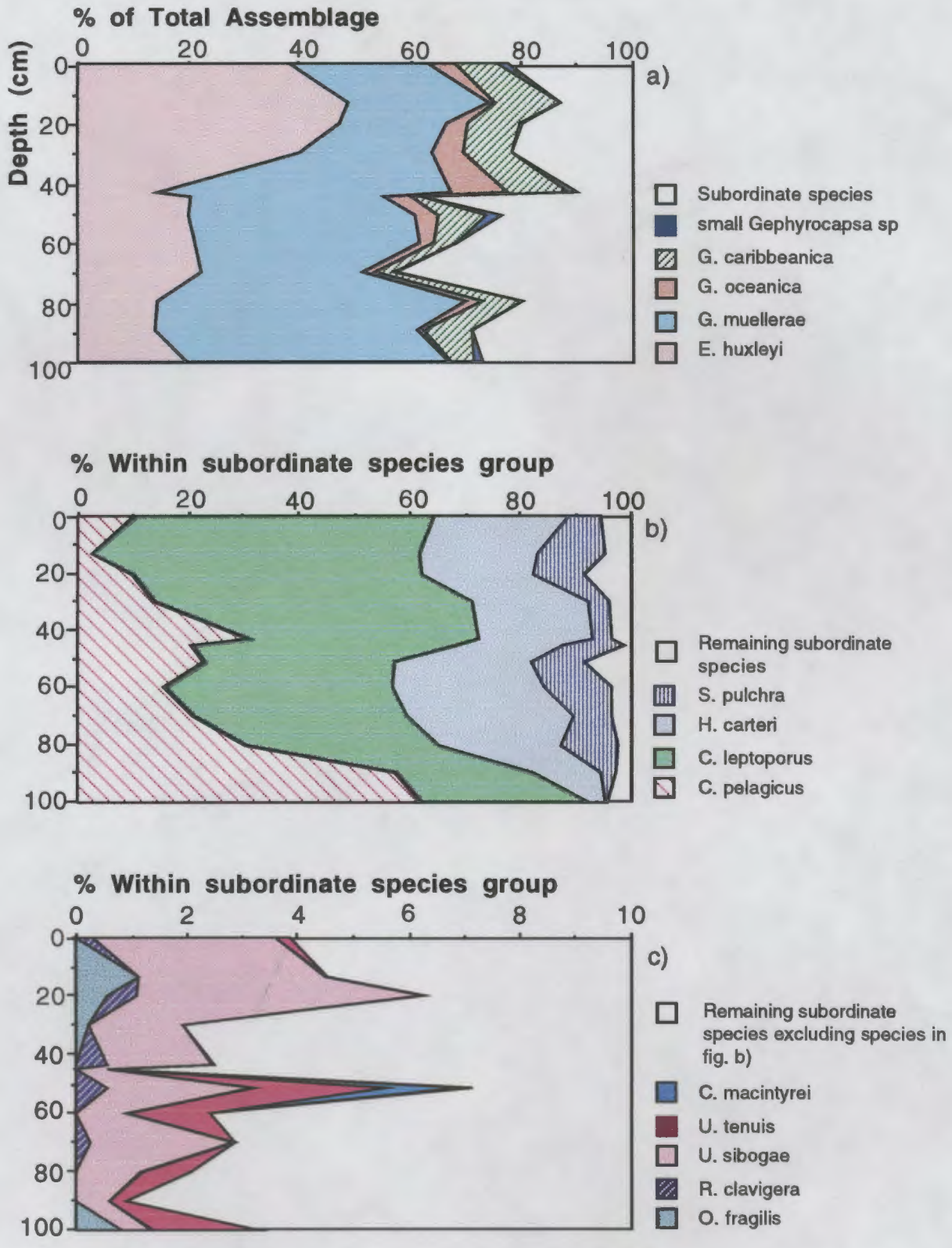


Fig. 35 Percentages of calcareous nannoplankton in core GC07 between 0cm - 100cm, illustrating the changes associated with the increased sedimentation rate between 60cm and 45cm.

Stratigraphy

The coretops for these cores have a majority of *G. muellerae* over *E. huxleyi* (Fig. 31) suggesting an age older than stage 4 (Thierstein et al., 1977; Weaver and Thomson, 1993). The absence of *G. caribbeanica* in high percentages in all cores suggest the sediments are younger than the stage 7/8 boundary and the rare occurrence of small *Gephyrocapsa* spp suggest an age younger than stage 7 (Weaver and Thomson, 1993).

The coretop of GC04 shows almost equal percentages of *G. muellerae* and *E. huxleyi* indicating an age at the stage 3/4 boundary (Thierstein et al., 1977; Weaver and Thomson, 1993), though a ^{14}C date at 5-8 cm gives an age of 3,160 yr BP (Samson, 1998). There is some evidence to support and early date of 11 ka for the reversal event between *G. muellerae* and *E. huxleyi* in this region, compared to the previously established date of 73 ka (Thierstein et al., 1977) as discussed below (GC07). However, the ^{14}C date of 3,160 yr BP is considered to be too young for this reversal event. It is possible dissolution has reduced the abundance of *E. huxleyi* in the coretop of GC04 leaving a slightly higher abundance of *G. muellerae*. Between the depths of 53cm and 50cm increases in *G. muellerae* and *G. caribbeanica* coupled with a reduction of *E. huxleyi* indicates an older age for the sediments at this depth, possibly stage 6 following the stratigraphy shown in Figure 16 (Weaver and Thomson, 1993).

Difference in abundances between *E. huxleyi* and *G. muellerae* in the remaining coretops (GC20, GC31, GC32, GC34, GC35) vary and are either the result of dissolution of *E. huxleyi* or erosion of younger sediments leaving an older sediment assemblage exposed. It is possible coretops for GC31, GC32 and GC34 reflect dissolution of *E. huxleyi* as the abundance differences between this species and *G. muellerae* are not great in comparison to GC20 and GC35 which show greater abundance variations, possibly due to erosion of younger sediments. The increase of *G. caribbeanica* in GC35 at 125cm coupled with the absence of *E. huxleyi* indicates a minimum age at the boundary of stages 7/8. Without ^{14}C dates for these remaining coretops it is not possible to determine if they are

Holocene where dissolution has decreased *E. huxleyi*, or older sediments where the Holocene has been removed.

Reworking and Dissolution

GC31 shows a peak of reworked species at 75cm accompanied by a reduction in all remaining species with the exception of *G. muellerae* (Fig. 31). The reworked species include *Reticulofenestra* spp, *C. macintyrei*, *Discoaster* sp., and *P. lacunosa*. As the assemblage above and below this depth is dominated by *G. muellerae* with the presence of *E. huxleyi* (i.e., indicates stage 5), the increase of reworked species at 75cm suggests a turbidite. Previous studies of core sediments from the same area have noted the common occurrence of turbidites and hiatuses (Wells and Connell, 1997; Passlow et al. 1997 and references therein).

Dissolution is evident in these cores and may reduced the abundance of *E. huxleyi* resulting in Holocene coretops dominated by *G. muellerae*. The rare occurrence of *Gephyrocapsa* spp which should be abundant in stages 6 and 7, may be the result of dissolution of these small fragile species, although the regular presence of the more delicate *U. sibogae*, combined with the occasional presence of *R. clavigera* and *Syracosphaera* sp., indicates dissolution is not the sole cause for the absence of small *Gephyrocapsa* spp in this region. Small *Gephyrocapsa* spp may reflect subtropical conditions as they negatively covary with *G. muellerae*, a subantarctic species (GC07 this study, Geitzenauer et al. 1976; Weaver and Pujol, 1988; Flores et al. 1997).

High resolution study of core GC07 from the South Tasman Rise.

Dissolution

The water depth at the location of GC07 is approximately 3307m and although above the lysocline for this region (Howard and Prell, 1994; Takahashi et al., 1981; Kolla et al., 1976; Constans, 1975) may still be affected by the Circumpolar Deep Water (CDW) mass, resulting in dissolution recognised in the sediments of GC07. Previous studies in the

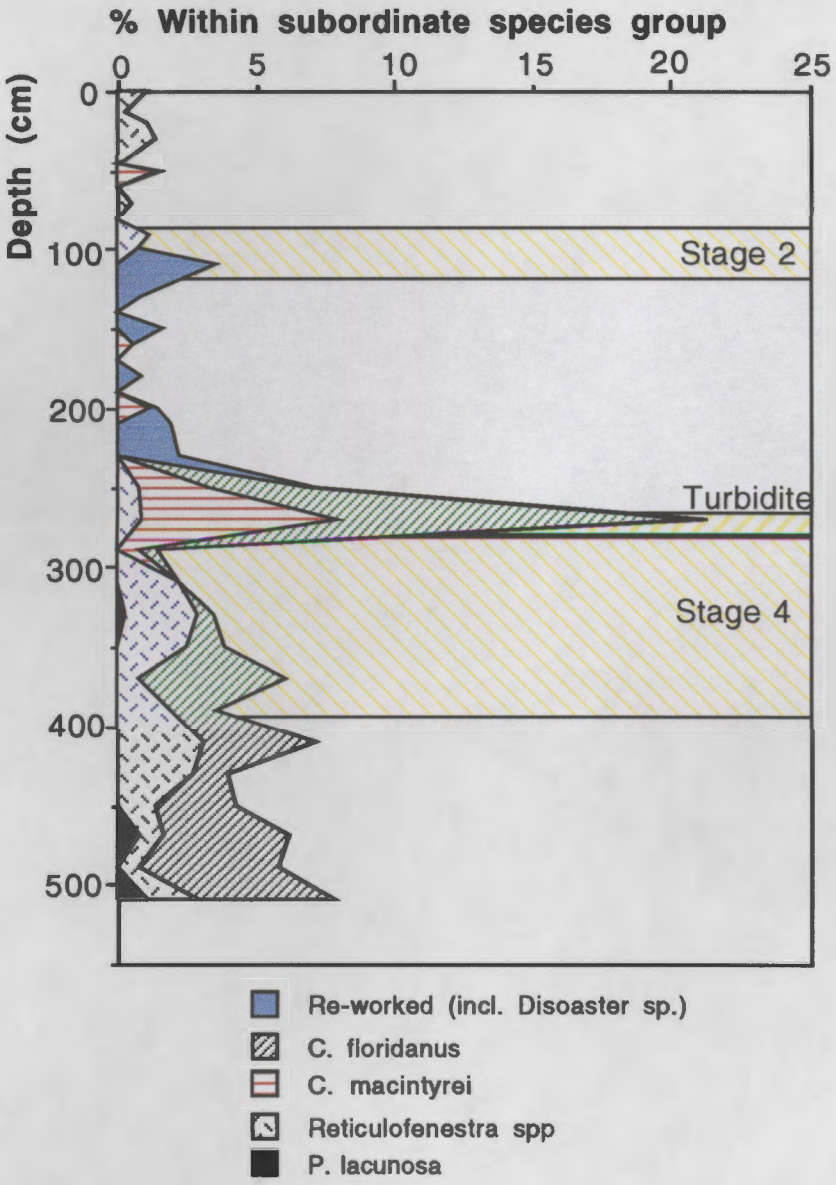


Fig. 36. Percentage within subordinate species group of re-worked species in core GC07, illustrating the turbidite event at 270cm.

same area have identified the CDW between the depths of 1600m and 4000m (Passlow et al., 1997).

The abundance of *E. huxleyi* in core GC07 (and those discussed above) is never more than 30% of the total assemblage suggesting dissolution, and possible erosion. A recent study east of Tasmania (44°S) showed percentages >60% for *E. huxleyi* in the top 20cm of a gravity core (Hiramatsu and De Deckker, 1997b). The difference between the two sites may reflect variation in initial assemblage composition. A tropical assemblage occurs to the east of Tasmania which would produce a higher abundance of the 'warm water' forms of *E. huxleyi*, which are preferentially preserved over the 'cold water' form. Dissolution of *E. huxleyi* coccoliths in sediment samples of GC07 shows the same pattern as documented in surface sediments (Chapter 5), i.e., dissolution of the 'T' elements often leaving only the central ring of the distal shield (Plate 5; Fig. 1) and where more complete coccoliths are present, they are heavily calcified, suggesting the 'warm water' form (Plate 5; Fig. 5).

The interpretation of the barren interval identified at 120cm of GC07 is problematic. Intervals barren of calcareous nannoplankton are usually associated with carbonate dissolution events, or high productivity of other phytoplankton groups diluting the calcareous nannoplankton, often indicating glacial maximums. Similar barren intervals in sediments above the CCD have been interpreted as movement of the PF equatorward of the site introducing polar waters (McIntyre et al., 1970). A migration of the PF by 8° equatorward in early stage 2 would be required to explain the barren zones by this mechanism, an unlikely scenario. The remainder of stage 2 includes species representative of subtropical waters (i.e., *U. tenuis*, *U. sibogae*, *G. caribbeanica* and *O. fragilis*), preceded by a peak of warm-water species at 130cm. Similarly, a core in the South Atlantic showed a barren interval in stage 2 with the PF poleward of that site during stage 2 (Gard, 1989b).

Reworking

The presence of reworked extinct species can be the result of a number of processes including: erosion; input from terrigenous sources during sea-level low stands; or, downslope transport (e.g., via a turbidite). The presence of reworked species between 50cm and 45cm, including *Sphenolithus* spp, *Discoaster* spp (Plate 5; Fig. 5), *Reticulofenestra* spp (Plate 5; Figs 6, 7 and 8), *C. floridanus* and *C. macintyrei* (Plate 5; Fig. 1) indicate reworking (Fig. 35), possibly by an erosional event. The peak of reworked species identified at 270cm (Fig. 36) correlates to a turbidite structure in the core-log. Evidence of downslope transport includes the presence of ascidian spicules, usually associated with shallow waters (Okada, 1992).

The reworked assemblages throughout the core include species of Miocene (*C. floridanus*), Pliocene (*R. pseudoumbilica*) and Pleistocene ages (*P. lacunosa* and *C. macintyrei*). Reworking of sediments may be associated with preferential sorting of the more robust larger coccoliths (e.g., *C. pelagicus, C. leptoporus* and *H. carteri*) and increases in these species can be used to confirm reworking. The lack of sorting of these species and the low percentages of reworked species indicates GC07 has not been greatly disturbed, with the exception of the turbidite event, and contains a fairly continuous record.

Stratigraphy

Reversal event of *E. huxleyi* and *G. muellerae*. The reversal in dominance between *Gephyrocapsa* spp and *E. huxleyi* is identified at approximately 40cm in GC07 with a ^{14}C age of 11 ka, in obvious conflict with the biostratigraphic age of 73 ka previously recorded for this reversal event (Thierstein et al., 1977). The reversal event between *G. caribbeanica* and *E. huxleyi* identified by Thierstein et al. (1977) is the equivalent to the reversal between *E. huxleyi* and *G. muellerae* found elsewhere (Wells and Okada, 1996; Flores et al., 1997). The date of 11 ka for the reversal of these two species in this region is possible, although considerably younger than previously recorded dates (Thierstein et al., 1977; Summerhayes et

al. 1995; Jordan et al., 1996; Flores et al. 1997). Thierstein et al. (1977; Fig. 2a, b) report a change in dominance between *E. huxleyi* and *'G. caribbeanica'* at levels above 73 ka, particularly in transitional and subpolar cores. Jordan et al. (1996) show that the reversal in dominance between these two species may occur at approximately 40 ka in regions of coastal upwelling. In the western Mediterranean, alternation in abundance peaks between the two are found between 73 ka and 47 ka (Flores et al., 1997). In the southeast Indonesian basins an age of 42 ka is indicated for the base of the *Emiliania huxleyi* acme based on ^{14}C dates (Biekart, 1989). The same study also recorded more recent extinctions for *G. ericsonii* (14 ka to 18 ka) than in southwest Pacific (59 ka;Li and Okada, 1985 *in* Biekart, 1989).

Differences in the age for the reversal event between *E. huxleyi* and *Gephyrocapsa* spp., marking the base of the *Emiliania huxleyi* acme zone, has been summarised by Jordan et al. (1996) as follows:

Emiliania huxleyi Acme Zone

Region	Duration (ka)	Reference
Tropical	0-85	Thierstein et al., 1977
Subtropical	?	
Temperate	0-73	Thierstein et al., 1977
Subantarctic	?	
Subarctic	?	
Antarctic	?	
Arctic	0-61	Gard, 1989b; Nowaczyk & Baumann, 1992.
Coastal upwelling	0-45	Summerhayes et al., 1995; Jordan et al., 1996

The evidence in this study suggests that this biostratigraphic event occurs at a younger age in the subantarctic region compared to other regions. Alternatively, the effects of dissolution may reduce the numbers of *E. huxleyi* and obscure the original datum event. In either case, the date of 73 ka for the reversal of these two species is not applicable in this region. Further cores sampled at high resolution for calcareous nannoplankton, coupled with ^{14}C dates would be required to resolve this question.

Supporting the argument that the reversal event occurs at a younger age in this region is the data for core V18-222 (38°S) south of Australia (Wells and Okada, 1996). Wells and Okada (1996) show a dominance of *G. muellerae* over *E. huxleyi* in stage 2 (between the radiocarbon dates of 11 ka and 41 ka), suggesting the reversal event for these two species lies somewhere between these dates. A second core from this region (Hiramatsu and De Deckker, 1997b) shows a dominance of *G. muellerae* over *E. huxleyi* occurring somewhere between stage 2 and 3 (12 ka to 58 ka). The position of the isotopic stages for this second core are inferred from planktonic foraminifera $\delta^{18}O$. In addition, the FO of *E. huxleyi* has been recorded at a much younger age in the subantarctic, 110 ka to 220 ka, compared to the FO in the Atlantic Basin, 250 ka to 270 ka (Geitzenauer, 1972). Extrapolating from this, the reversal date between the dominance of *E. huxleyi* and *G. muellerae* at an younger age in the subantarctic is possible.

Small *Gephyrocapsa* spp. The increase of small *Gephyrocapsa* species between 510cm and 390cm probably represents stage 5, with the peak at 390cm interpreted as stage 5a. The oscillating pattern of this group is considered to reflect the substages of stage 5. GC07 may record stages 5a to 5d only with stage 5e below the depth of 510cm. Stage 5e is recognised as the warmest interglacial interval and increases of subtropical species at 510cm may indicate the proximity of stage 5e below this depth.

The peak of small *Gephyrocapsa* spp at 310cm is difficult to interpret. Small *Gephyrocapsa* spp indicate warm interglacial intervals although for this sample (310cm) the remaining species indicate a cool glacial interval, e.g., high percentages of subantarctic species (*C. pelagicus* and *G. muellerae*) and low percentages of subtropical species (*C. leptoporus, H. carteri, U. sibogae, U. tenuis, R. clavigera* and *S. pulchra*).

Paleoceanography

Paleoceanography interpretations are based on the abundance variations among species recognised as preferring subtropical waters, including *H. carteri, C. leptoporus, S. pulchra, O. fragilis, R. clavigera, U. sibogae* and *U. tenuis*, and those preferring subantarctic waters, *C. pelagicus* and *G. muellerae* (Fig. 34).

Oxygen Isotope Stage 1. Stage 1 shows higher percentages of subtropical species with lower percentages of subantarctic species (*C. pelagicus* and *G. muellerae*) compared to stage 2, interpreted as the presence of subtropical waters over the core site for this interval. The position of the STF, which separates subtropical assemblages to the north from subantarctic assemblages, is inferred as poleward of GC07 for this interval based on the calcareous nannoplankton assemblage in the sediments. A marginal equatorward shift to its present-day position is reflected by the slight decrease of subtropical species in the upper 20cm of the core. This is in agreement with previous studies in the Southern Ocean based on faunal migrations of planktonic foraminifera (Howard and Prell, 1992) and radiolarian assemblages (Morley, 1989). In contrast, Wells and Connell (1997) suggest the STF was equatorward of 46°S from early stage 1 through to 10 ka, when it moved poleward to its present-day position. However, these authors note the $\delta^{18}O$ and paleotemperature record may be distorted due to disturbance of the cores used for their study.

Variability in $\delta^{18}O$ at GC07 between approximately 55cm and 45cm correlates with the change in dominance between *G. muellerae* and *E. huxleyi*, increases in *C. pelagicus*, and decreases in *C. leptoporus* (Fig. 34). These results indicate a cooling event which ^{14}C dates suggest coincides with the Younger Dryas event. Higher resolution sampling between the depths of 60cm and 40cm may show changes in the ratio of *C. pelagicus* and *C. leptoporus* documenting the calcareous nannoplankton response to the Younger Dryas in this region.

Oxygen Isotope Stage 2. The increase in *C. pelagicus* and *G. muellerae* and reduction in subtropical species between 110cm and 70cm reflects a cooler interval during the LGM. The interpretation of a cooler interval is supported by the increased values of $\delta^{18}O$ and the decreased values of $\%CaCO_3$ for the same interval. The barren zone identified at 120cm is associated with increased dissolution of coccoliths. Similarly, Passlow et al. (1997) identified stage 2 as a dissolved interval in a core collected from the South Tasman Rise. The calcite lysocline in the southeast Indian Ocean has been documented at 600m shallower in stages 2 and 4 compared to its present-day depth (Howard and Prell, 1994).

Calcareous nannoplankton assemblages imply that the STF was equatorward of GC07 during stage 2, introducing subantarctic waters over the site. Decreases of subtropical species are greater for stage 2 than stage 4 suggesting the STF was farther north during stage 2 compared to stage 4. Previous research supporting this interpretation include the location of the STF adjacent to, or immediately south of 38° during stage 2 in the same region (Wells and Connell, 1997); and a shift of oceanic fronts equatorward by 5° to 7° during glacial intervals in the southern Indian (Morely, 1989).

Between 110cm and 100cm an increase in some subtropical species suggest that changes in the floral assemblage precede changes in the $\delta^{18}O$ record. Similarly, previous studies in the southern Indian Ocean (Howard and Prell, 1992) and the North Atlantic (Gard and Backman, 1990) have noted faunal migrations precede the $\delta^{18}O$ record.

Oxygen Isotope Stage 3. The lower percentages of subtropical species (particularly *H. carteri*) and the domination of *C. pelagicus* over *C. leptoporus* between 250cm and 130cm indicate stage 3 is a cooler interglacial than stages 1 and 5. Higher percentages of *G. caribbeanica*, considered to represent transitional rather than subtropical water masses, in stage 3 also suggests cooler conditions compared to stages 1 and 5 (Fig. 37). *C. pelagicus* shows higher percentages than *C. leptoporus* from early

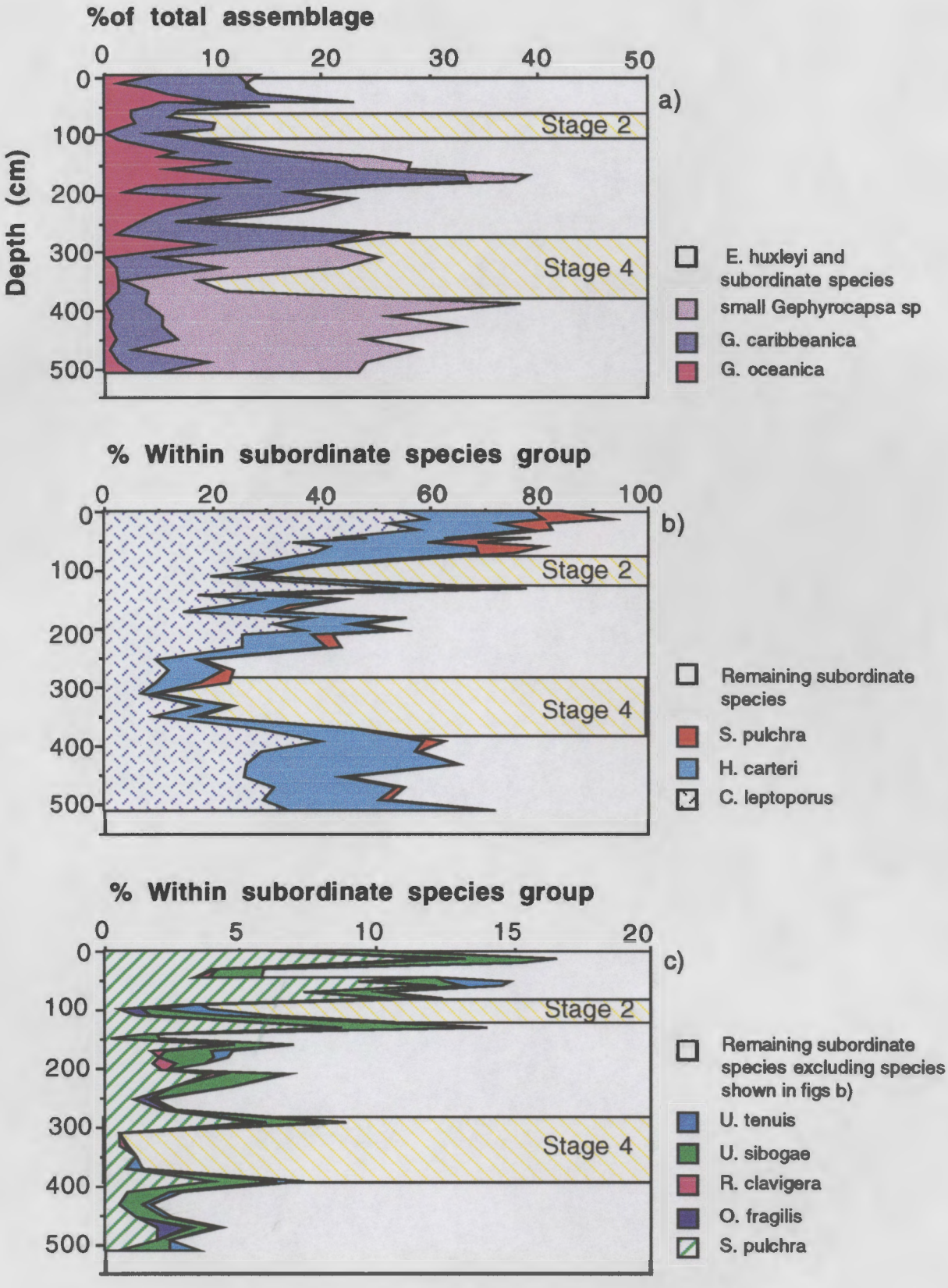


Fig. 37. Percentages of calcareous nannoplankton in core GC07. a) subtropical to transitional gephyrocapsids; b) more resistant subtropical to transitional subordinate species; c) less resistant subtropical to transitional subordinate species.

stage 3 to the depth of 130cm where it decreases and *C. leptoporus* dominates. At the same depth (130cm) $\delta^{18}O$ decreases, $\%CaCO_3$ and subtropical species (*H. carteri*, *S. pulchra* and *U. sibogae*) increase and *G. muellerae* decreases, indicating a warming interval in late stage 3.

Calcareous nannoplankton assemblages suggest the STF shifted poleward between stages 4 and 3 introducing subtropical waters to the site, however, as stage 3 is interpreted as a cooler interglacial than stages 1 and 5, the location of the STF may have been equatorward of the positions inferred for stages 1 and 5. There is some evidence to suggest the site was subject to fluctuations of the STF across the location during stage 3. Increases in subtropical species and decrease in subantarctic species may indicate a poleward shift of the STF in early stage 3 at 230cm and in late stage 3 at 170cm and 130cm (Fig. 34).

Oxygen Isotope Stage 4. The increase of the subantarctic species, *G. muellerae* and *C. pelagicus*, accompanied by a reduction in the percentages of subtropical species between the depths of 390cm and 270cm (Fig. 34) is the criteria for identifying stage 4. Based on calcareous nannoplankton, the STF was equatorward of GC07 during stage 4, introducing subantarctic waters to the location.

Between 370cm and 310cm the $\%CaCO_3$ remains high (Fig. 32) indicating an interglacial interval (i.e., a warm interval resulting in high productivity and high $\%CaCO_3$ preserved in the sediments). This is in contrast to the calcareous nannoplankton assemblage which show higher percentages of subantarctic species (*G. muellerae* and *C. pelagicus*) and lower percentages of subtropical species for the same interval, with the exception of a peak of small *Gephyrocapsa* spp at 310cm. Quaternary sediments in the Southern Ocean are sometimes barren of coccoliths even at high levels of $\%CaCO_3$ (Gard and Crux, 1991) indicating calcareous nannoplankton production is not the only source of biogenic carbonate.

Oxygen Isotope Stage 5. The oscillating and opposing cycles of *G. muellerae* and small *Gephyrocapsa* spp in stage 5 may represent the substages of stage 5 with *G. muellerae* representing cool intervals and small *Gephyrocapsa* spp warm intervals. The increase in small *Gephyrocapsa* spp during stage 5 (Fig. 34) has been observed in other regions (Gard, 1989a; Weaver, 1993; Weaver and Thomson, 1993; Beaufort and Giraudeau, unpub.; Jordan, et al., 1996; Flores et al., 1997; Flores et al., in press). A previous study in this region found minimal numbers of small gephyrocapsids (*'G. aperta'*) and an increase of 'small placoliths' in stage 5 (Hiramatsu and De Deckker, 1997b), although the 'small placoliths' may be small gephyrocapsids with no central bridge structure.

The peak of small gephyrocapsids at 390cm may represent the warm substage 5a. The warming event at this depth is also marked by the reduction of *G. muellerae* and *C. pelagicus* and the increase of *C. leptoporus, S. pulchra U. sibogae* and *U. tenuis*. The percentages of these species indicate stage 5a is warmer than previous substages of stage 5. Similarly, previous studies recorded highest peaks of small gephyrocapsids in stage 5a in the North Atlantic (Gard and Backman, 1990) and peaks of small placoliths in stage 5a with lower peaks in stage 5e in the South Indian Ocean (Gard, 1989b). The low calcareous nannoplankton abundances in the North Atlantic in stage 5e may be due to dilution by ice rafted debris during the deglaciation.

Not all subtropical species show an increase in stage 5, i.e., *G. oceanica* and *G. caribbeanica*. The gephyrocapsid group have undergone recent evolutionary changes (Matsuoka and Okada, 1990; Samtleben, 1980) and changes in environmental niche (Gietzenauer, 1972) and this appears to be reflected in GC07. Although *G. caribbeanica* and *G. oceanica* percentages are higher for stages 1 and 3 (interglacials), stage 5 shows lower percentages, indeed, lower than for stage 4, a glacial interval. Changes within this group (e.g., environmental preferences, evolutionary or morphological change) appear to have occurred between stages 4 and 5, in this region.

The higher percentages of subtropical species for stage 5 indicates the position of the STF was poleward of GC07 for this interval.

Species

A number of individual species show distributional patterns downcore that can be related to glacial and interglacial cycles and are reliable proxies for the paleoceanographic interpretation in downcore studies. For example, *C. leptoporus* and *H. carteri* show increases in interglacial intervals and decreases in glacial intervals (Fig. 37), suggesting they may be warm-water indicators. Similar results have been recorded in the South Atlantic and south Indian Ocean (Gard, 1989b). *C. pelagicus* and *G. muellerae* record the opposite pattern where increases reflect glacial intervals.

C. pelagicus and *C. leptoporus* negatively covary in stages 1 to 4 (Fig. 34) with *C. leptoporus* representing subtropical waters and *C. pelagicus* subantarctic waters, as seen in previous Southern Ocean studies (Gietzenauer, 1969; Gard, 1989b; Wells and Okada, 1996). The highest percentages for *C. leptoporus* occur in stage 1 suggesting this is the warmest interval in GC07. Similarly, *C. leptoporus* was dominant in stage 1 in the South Atlantic (Gard and Crux, 1991). In contrast, stage 1 in high northern latitudes shows maxima of *C. pelagicus* (Gard, 1989a; Baumann and Matthiessen 1992; Nowaczyk and Baumann, 1992; Samtleben et al. 1995b; Baumann, 1995).

In GC07 the negative covariance between *C. leptoporus* and *C. pelagicus* for stage 5 is not well defined, and it is possible the oscillating climatic conditions (reflected by the substages) affected the production of these two species for this interval. These species occupy the narrow transitional zone in the living assemblages of the northern hemisphere, where small changes in environmental parameters would effect their production (Gietzenauer, 1972). It is possible the transitional zone in the Southern Hemisphere was not always present in stage 5. The occasional absence of

the transitional zone in the Southern Hemisphere has been suggested in previous studies of this region (McIntyre et al., 1970). In the North Atlantic *C. pelagicus* is sparse or absent in stage 5, interpreted as this interval being too warm for this species (Baumann, 1995).

Gephyrocapsids representing subtropical environments with higher abundances during interglacial intervals include *G. caribbeanica*, small *Gephyrocapsa* spp and *G. oceanica* (Fig. 34). *G. oceanica* and *G. caribbeanica* have peaks in stage 1 and 3 of GC07 (Fig. 37). In stage 5 small *Gephyrocapsa* spp dominate (Fig. 37) and may dilute the production of *G. caribbeanica* and *G. oceanica*. Alternatively, species within this genus may have changed their environmental preferences through time.

G. caribbeanica, in addition to showing peaks in glacial intervals (Wells and Okada, 1996; Gietzenauer, 1969), peaks in stage 5e in the subantarctic (Gietzenauer, 1972). This eurythermal species may have preferred cooler waters in stage 5 and warmer waters in stages 1 and 3. However, the differences between various studies of *G. caribbeanica* may reflect mis-identification of this species. The confusion associated with the identification between *G. caribbeanica* and *G. muellerae* has been noted previously (Flores et al., 1997; Okada and Wells, 1997). On this basis, comparison with previous studies for these species is approached with caution.

G. muellerae shows negative covariance with small *Gephyrocapsa* spp. in stage 5 where *G. muellerae* represents cooler substages for this interval (Fig. 34). The relationship between these two species is not as clear in stages 1 to 3 and may be further evidence of evolutionary and/or environmental changes within these species.

Higher abundances of *G. oceanica* in stages 1 and 3 of GC07 indicates this species preference for subtropical waters associated with interglacial intervals. However, abundance variations of this species may be associated with factors other than temperature, e.g., salinity

(Knappertsbuch, 1993). Due to low abundances in the subantarctic combined with its possible environmental and evolutionary changes, *G. oceanica* is not considered a reliable paleoclimatic indicator in this study.

U. tenuis, *O. fragilis* and *R. clavigera* are considered to represent subtropical rather than transitional waters in this study as noted previously (McIntyre and Bé, 1967; Nishida, 1986; Winter et al., 1994). Although, they have been recorded previously in transitional waters of the North Pacific (Okada and Honjo, 1973). Percentages of these species are low throughout core GC07, with *U. tenuis* showing highest percentages in stage 1 and a peak in stage 5 corresponding to the suggested interval of stage 5a (Fig. 34). Highest percentages for *O. fragilis* are found in the Holocene with a second peak in stage 5. The peaks of *O. fragilis* and *U. tenuis* in stage 2 are not readily explained. *R. clavigera* shows highest percentages in stage 3. These three species have been recorded previously in transitional waters (Winter et al., 1994; Okada and Honjo, 1973).

D. Summary

Stratigraphy

Oxygen isotope stages 1 to 5 are recognised in core GC07 (Figs 32, 34) with some evidence for substages in stage 5. Oxygen isotope stages 1 and 2 are interpreted on the basis of calcareous nannoplankton assemblages and variations in $\%CaCO_3$ and $\delta^{18}O$ values, supplemented by ^{14}C dates. A reversal in dominance between *G. muellerae* and *E. huxleyi* occurs at 40cm at ^{14}C date of approximately 11 ka. This date may represent the age of the reversal event in the high latitudes of the Southern Ocean compared to the previously established age of 73 ka. Identification and interpretations of stages 3, 4 and 5 are tentative due to the lack of supporting data (e.g., $\delta^{18}O$). The $\%CaCO_3$ stratigraphy appears to correlate well with changes in calcareous nannoplankton assemblages for stages 1 through to 3 although is not clear for stages 4 and 5. As high $\%CaCO_3$ has

been reported in previous studies where calcareous nannoplankton are absent $\%CaCO_3$ is not considered to be a useful paleoceanographic proxy without further supporting data.

Paleoceanography

The STF is interpreted as moving equatorward during glacial intervals introducing subantarctic waters at the location of GC07 and poleward during interglacial intervals introducing subtropical waters to the site, based on changes in calcareous nannoplankton assemblages, i.e., a subtropical assemblage dominates during interglacial intervals and a subantarctic assemblage dominates during glacial intervals.

Species

A number of species provide useful paleoceanographic information. These include *C. pelagicus* (representing cool intervals) and *C. leptoporus* (representing warm intervals) which show a clear relationship with temperature. The ratio between these two species can be used to identify glacial and interglacial intervals in downcore sequences. The negative covariance between these two species is evident in stages 1 through to 4 in GC07 though obscured in stage 5 where the effects of oscillating climatic conditions effect the narrow ecological niche of these two species. Similarly, the abundance pattern for *H. carteri* can be related to temperature where higher abundances indicate interglacial intervals.

High abundances of *G. caribbeanica* and *G. oceanica* occur during interglacial intervals stages 1 and 3. In stage 5 the high abundance of small *Gephyrocapsa* spp may dilute the presence of *G. caribbeanica* and *G. oceanica,* or may reflect evolutionary and environmental changes associated with these species. High abundances of *G. muellerae* correlate with glacial intervals.

The most reliable species as indicators of paleoceanographic change in this region include *C. leptoporus; C. pelagicus; G. muellerae; H. carteri* and small *Gephyrocapsa* spp (especially in stage 5).

Oxygen Isotope Stages

Calcareous nannoplankton assemblages indicate stages 1 and 5 are the warmest interglacials and stage 3 a cooler interglacial. Stage 2 is interpreted as a cooler glacial interval than stage 4. There is some evidence for a Younger Dryas event between the intervals of 60cm and 40cm and abundance variations of *C. pelagicus* and *C. leptoporus* may identify this event with further high resolution sampling between these intervals. Variation of abundances for small *Gephyrocapsa* spp and *G. muellerae* in stage 5 may represent substages for this interval where small *Gephyrocapsa* spp indicate warmer intervals.

Chapter Seven Summary

A. **Introduction**

B. **Discussion**

1. Water column
2. Surface sediment
3. Core sediment
4. Comparison of water column data and surface sediment data
5. Comparison of surface sediment data and core sediment data

C. **Conclusions**

1. Limitations of this study

A. Introduction

The focus of this study is the paleoceanography of the Australian Sector of the Southern Ocean. This research was carried out using samples from the water column, surface sediments and downcore sequences. The first part of the study documents the distribution of calcareous nannoplankton in the modern environment. Specifically, it identifies the species living in the region, defines biogeographic zones based on calcareous nannoplankton assemblages and relates changes in the assemblages to physico-chemical properties of the surface water masses and hydrological fronts in the region.

The second part of this study is a comparison between assemblages in the water column and underlying surface sediments, the differences between the two and identification of processes responsible for those differences, including dissolution, erosion, reworking and seasonal production.

The third part of the project examines calcareous nannoplankton assemblages in samples from a Late Quaternary core sequence and compares them to surface sediment and living assemblages to determine the paleoceanography of the region.

B. Discussion

Water Column

The water column samples collected between 41°S and 63°S from the upper 200m of the water column could be divided into five biogeographic zones based on assemblages of calcareous nannoplankton and their association with physico-chemical environments (temperature, nutrients and salinity). These assemblages and biogeographic zones are interpreted as:

a) tropical to subtropical zone, defined by the presence of tropical and subtropical species, e.g., *E. huxleyi* 'warm water' form, *D. tubifera* and *Gephyrocapsa* spp. This zone is unique in this study to the east coast of Tasmania where the poleward-flowing East Australian Current transports tropical waters into the region;

b) subtropical to transitional zone, north of the STF to the east of Tasmania which is dominated by *E. huxleyi* 'warm water' form, with *U. tenuis* as the second most dominant species. This region is a mixing zone of surface and subsurface water, between the warm waters of the poleward-flowing Zeehan Current and colder waters to the south;

c) transitional zone, between the STF and SAF south of Tasmania, identified by the domination of *E. huxleyi* 'cold water' form with the presence of *E. huxleyi* 'polar' form and *C. leptoporus* as the second most dominant species. This zone is transitional between the subtropical and subantarctic zones;

d) subantarctic zone, identified between the SAF and PF, comprised of a monospecific assemblage dominated by *E. huxleyi* 'cold water'; and

e) antarctic zone, identified south of the PF to 61°S, dominated by *E. huxleyi* with the presence semi-calcified polar species.

The distribution of some species in the water column is associated with hydrographic fronts and water masses, and is potentially useful for the interpretation of paleoceanography. For example, *E. huxleyi* 'warm water' form, *Syracosphaera* spp, *G. muellerae* and *U. tenuis*, north of the STF, indicate subtropical water masses. High percentages of *C. leptoporus* located south of the STF indicate transitional water masses.

Surface Sediment

Only eight of 45 surface sediment samples showed a majority of *E. huxleyi* over *Gephyrocapsa* spp, i.e., a potential age of 73 ka or younger based on established calcareous nannoplankton biostratigraphy, one of which is confirmed as Holocene (GC07) through ^{14}C dating. The ^{14}C date for GC04 shows a Holocene age for this coretop despite *G. muellerae* being more abundant than *E. huxleyi*, possibly due to preferential dissolution of *E. huxleyi*. The low abundance of *E. huxleyi* in coretops may be due to dissolution, erosion and reworking of sediments in the region.

The surface sediment assemblage, although different from the five assemblages identified in the water column, is most similar to the subtropical to transitional assemblage north of the STF in the water column. The poleward extent of abundant coccoliths in surface sediments is between 54°S and 55°S where seabed dissolution and high productivity of siliceous microfossils increases.

The most noticeable feature of the surface sediment assemblage is the presence of subtropical species (*U. tenuis*, *S. pulchra* and *H. carteri*) as far south as the PF zone, including taxa not present in the water column. Some of these taxa have been previously described as warm-water species, susceptible to dissolution (e.g., *U. sibogae*, *R. clavigera* and *O. fragilis*). The presence of these species within the PF zone can be interpreted a number of ways: they are more resistant to dissolution and can tolerate lower temperatures than previously documented; erosion of more recent sediments has exposed an assemblage from a warmer, early Holocene interval; or their presence reflects production in seasons other than austral summer (during which water column sampling was carried out).

Erosion of younger sediments leaving an assemblage reflecting a warmer, early Holocene interval is the likeliest explanation for these distributions. There is no evidence to suggest temperature requirements for these species have changed and their biogeographic zones identified in the water column appear to be similar to those documented in earlier studies. With the exception of *H. carteri*, these species are not considered to be preferential preserved, and their presence in surface sediments of the PF zone indicates dissolution is not severe.

Seasonal production and resistance to solution may account for the high abundance of *G. muellerae* in surface sediments as far south as the PF zone, despite its absence in overlying water masses. There is some evidence suggesting this species prefers cooler water masses and may have its highest production in seasons other than austral summer. However, subtropical species in subantarctic waters should have their highest production in austral summer.

Dissolution and reworking are likely to be secondary factors affecting the assemblage, reducing its abundance and diversity. Reworking is evident by small percentages of extinct species in most samples, and may in part explain the increase of *H. carteri* near the PF zone.

The effects of erosion, dissolution and reworking alter the preserved assemblages' relationships with overlying hydrographic features. However, increases of *C. pelagicus* and *H. carteri* and a decrease of *C. leptoporus*, may represent changes in nutrients at the STF.

Core Sediments

Two main assemblages were identified in downcore sediments of GC07, mainly reflecting subtropical and subantarctic biogeographic zones. The subtropical assemblage is identified by high abundances of *C. leptoporus, H. carteri, G. caribbeanica, G. oceanica* and small *Gephyrocapsa* spp, as well as minor warm-water species (*U. sibogae, U. tenuis, R. clavigera* and *O. fragilis*). This assemblage is related to subtropical water masses north of the STF. The second assemblage is associated with subantarctic water masses and includes high abundances of *G. muellerae* and *C. pelagicus*.

Two glacial and three interglacial intervals are recognised based on the variation in abundance of the calcareous nannoplankton assemblages, ^{14}C dates, $\delta^{18}O$ data and $\%CaCO_3$. These intervals are interpreted as oxygen isotope stages 1 to 5. Alternating peaks of small *Gephyrocapsa* spp and *G. muellerae* appear to represent the substages of stage 5, with the small *Gephyrocapsa* spp indicating the warmer substages.

A number of species including *H. carteri, G. muellerae, C. leptoporus, C. pelagicus* and small *Gephyrocapsa* spp show cyclical patterns between glacial and interglacial intervals and are considered as reliable paleo-indicators for climatic change in this region.

The Subtropical Front is interpreted as equatorward of GC07 during isotopic stages 2 and 4, and poleward of the location during isotopic stages 1, 3 and 5.

Comparison of Water Column Data and Surface Sediment Data

The calcareous nannoplankton assemblages identified in the surface and subsurface waters of the region are partly reflected in the surface sediments below.

The differences between the living and preserved calcareous nannoplankton assemblages are likely to be predominantly the result of erosion, exposing an assemblage from a warmer early Holocene interval. The presence of warm-water, more fragile species in surface sediments below subantarctic waters indicates dissolution is not severe although is recognisable by the overall reduction in abundance and diversity, the etching of coccoliths present, and the preferential preservation of *E. huxleyi* 'warm water' form over the more fragile 'cold water' form.

Seasonal productivity does not readily explain the presence of warm-water species within surface sediments of the PF zone, as it is unlikely they would have their highest production in this region in seasons other than austral summer.

Dissolution and reworking contribute to preferential preservation of the more robust forms including *C. leptoporus, H. carteri, S. pulchra, E. huxleyi* 'warm water' form and *G. muellerae*. The preferential preservation of *E. huxleyi* 'warm water' form over *E. huxleyi* 'cold water' form enhances its abundance in surface sediments. Comparisons of the 'warm water' and 'cold water' forms between living assemblages and surface sediment assemblages should be approached with caution.

C. leptoporus shows highest abundances in the living assemblage in the transitional zone south of the STF, compared to the surface sediment assemblage where it is the third most dominant species in the subtropical zone. Preferential preservation is considered to contribute to the high abundance of *C. leptoporus* in surface sediments, which may obscure its

relationship to the biogeographic zones identified in the living assemblages.

S. pulchra, U. tenuis and *G. muellerae* show a preference for the subtropical zone in the living assemblages and their presence in the surface sediment assemblage near the PF zone suggests a subtropical assemblage at this location.

Comparison of Surface Sediment Data with Sediment Core Data

Dissolution and reworking partly explain the composition of assemblages in the downcore sediments. The preferential preservation of more robust species identified in the surface sediments (*H. carteri, G. muellerae, C. leptoporus, E. huxleyi* 'warm water' form, *C. pelagicus*, and to a lesser extent *S. pulchra*) is evident in downcore sequences, where they are the dominant species. These species show distinct patterns between glacial and interglacial intervals.

The covariance between *C. pelagicus* and *C. leptoporus* in the downcore samples show high abundances of *C. leptoporus* during interglacial intervals and high abundances of *C. pelagicus* during glacial intervals. The higher abundances of *H. carteri*, and to a lesser extent *S. pulchra*, during interglacial intervals, confirms these species preference for warmer climatic intervals.

G. muellerae is identified as preferring a subtropical environment in the living assemblage and supports the hypothesis of a subtropical to transitional assemblage in surface sediments. In comparison, the downcore sediments show high abundances in glacial intervals for *G. muellerae* and the possibility this species has changed its temperature requirements through time must be considered.

It has been established the surface sediment assemblage reflects a subtropical environment as far south as the PF zone and does not directly

relate to present day hydrographic parameters south of the STF with some minor exceptions. In contrast, the assemblages preserved in downcore sediments reflects long-term changes in hydrographic conditions over time where the alternation between subtropical and subantarctic biogeographic zones correlate to glacial and interglacial intervals. The longer accumulation time for sediments in downcore samples obscures short-term effects, e.g., seasonal production, localised dissolution and reworking related to short-term bottom current movements which may be recognisable in surface sediments (e.g., higher abundances of *H. carteri* associated with changes in nutrient levels).

C. Conclusion

The five living assemblages identified in the water column can be associated with biogeographic zones defined by separate surface and subsurface water masses and hydrographic fronts in the region. The surface sediment assemblage reflects the living assemblage found in the subtropical zone which has been altered through dissolution, erosion and reworking. The surface sediment assemblage cannot be directly associated with overlying surface water masses or hydrographic fronts, with a few minor exceptions at the STF. The results from the two data sets identify key sedimentation processes that effect the preservation of calcareous nannoplankton and can be related to the assemblages identified in downcore sediments. The downcore assemblages clearly define oscillations between glacial and interglacial intervals with variations in abundance of a number of species recognised as temperature related including *C. leptoporus*, *C. pelagicus*, *G. muellerae*, *H. carteri*, and to a lesser degree, *S. pulchra*, identified in the surface sediment assemblage as preferential preserved.

Limitations of this study

There are a number of limitations to the research carried out in this study. For example, the living flora was sampled during a single

season, austral summer. This strategy does not reflect the seasonal production of some species, and may lead to misrepresentation of biogeographic zones of living calcareous nannoplankton assemblages. Further sampling of the water column in the Southern Ocean over longer time intervals (preferably a minimum of 12 months) via the use of sediment traps would overcome this shortfall in the data sets.

A second limitation is recognised by the lack of ^{14}C dates for surface sediment samples. The majority of surface sediment samples show *G. muellerae* dominant over *E. huxleyi* and, without ^{14}C dates, are considered to be older than 73 ka based on established calcareous nannoplankton biostratigraphy. However, the ^{14}C date for GC04 indicates the possibility of surface sediments dominated by *G. muellerae* as Holocene in age. With further ^{14}C dating the extent of dissolution of *E. huxleyi*, resulting in the domination of coretops by *G. muellerae* with a Holocene age, can be established and would determine the validity of the reversal event as an accurate biostratigraphic datum event in this region.

Oxygen isotope stratigraphy is limited to the upper 150cm of core GC07, being the only available data. Without isotope stratigraphy to the base of the core, isotopic stages 4 and 5 remain tentative.

The possibility that some species, e.g., gephyrocapsids, have changed their environmental preferences over time can not be discounted. In addition, previously documented temperature preferences of species may not apply to this region. Further sampling of the water column in the Southern Ocean to establish the environmental niche of living coccolithophore species (in particular temperature), would help to resolve these uncertainties. Seasonal sampling via sediment traps in this region is considered to be a high priority.

Finally, there are limitations associated with the sampling of a single core. Data from additional cores in the same region would confirm the

results of this study, add information with regard to possible evolutionary and environmental changes of species through time and determine the validity of the *E. huxleyi/G. muellerae* reversal event as a useful biostratigraphic datum event in the Southern Ocean. The location of GC07, adjacent to the STF, precludes the interpretation of the extent of latitudinal movement of hydrographic fronts and associated surface and subsurface water masses between glacial and interglacial intervals. Further samples from cores located either side of present-day front locations, at greater distances from these fronts, would provide this information.

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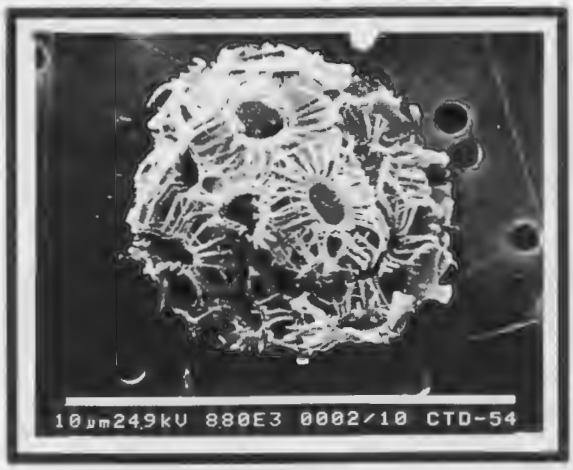
PLATE 1

Figure 1

Figure 2

Figure 3



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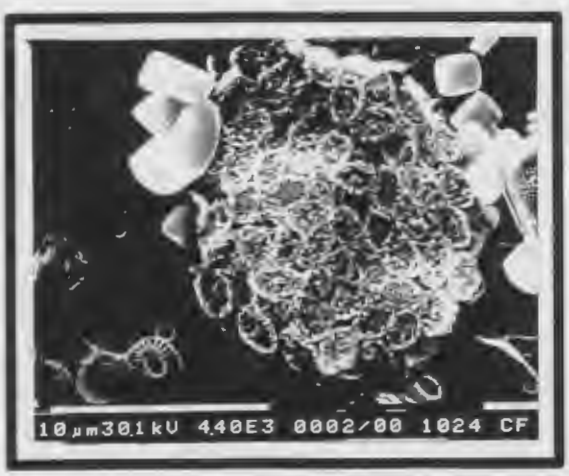


Figure 5

Figure 6

Figure 7

Figure 8

PLATE 2

Figure 1

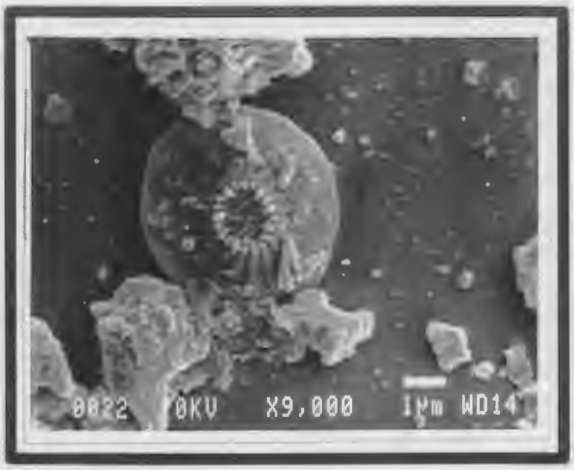


Figure 2

Figure 3

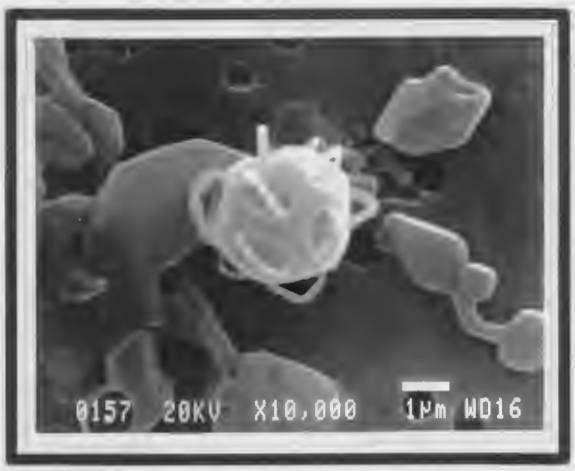
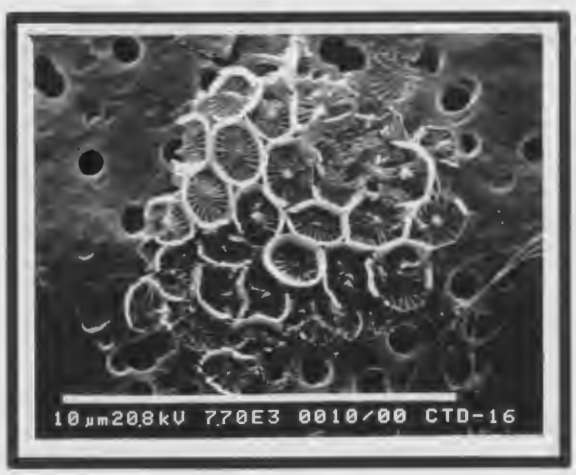


Figure 4

Figure 5



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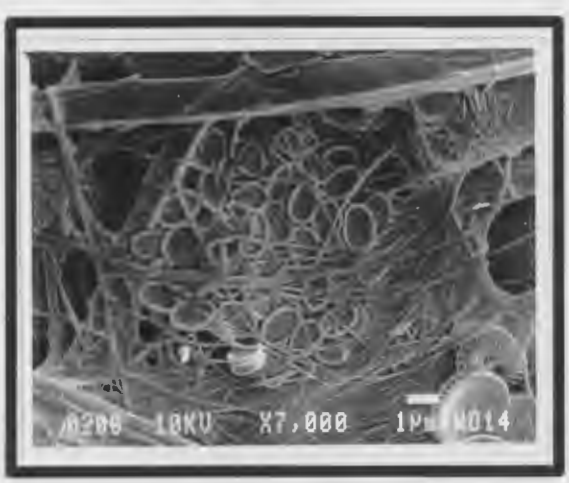

Figure 7

Figure 8

PLATE 3

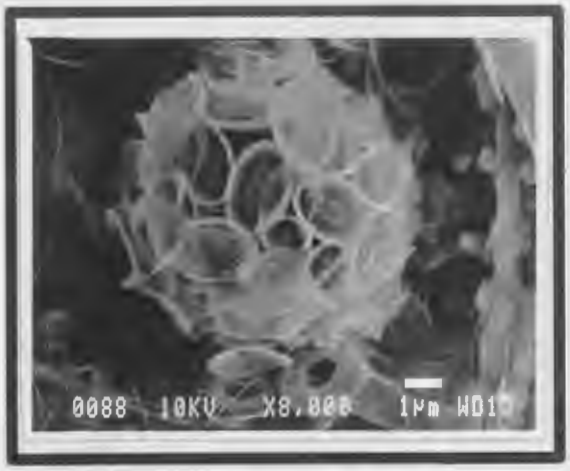

Figure 1

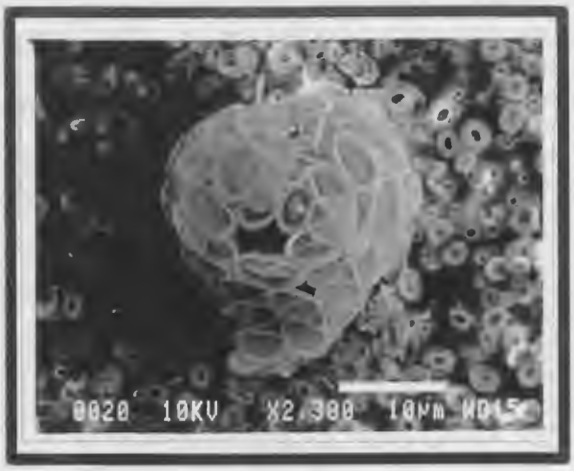

Figure 2

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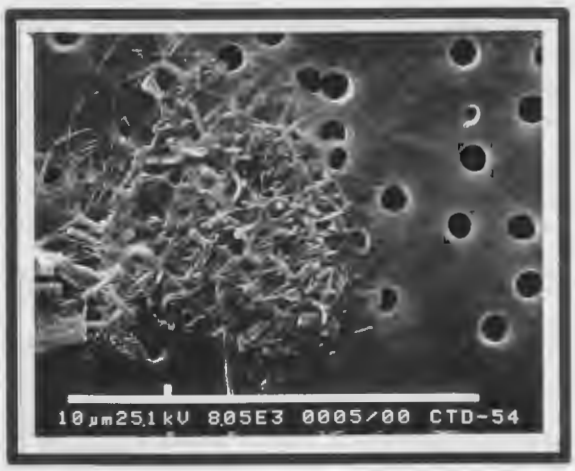

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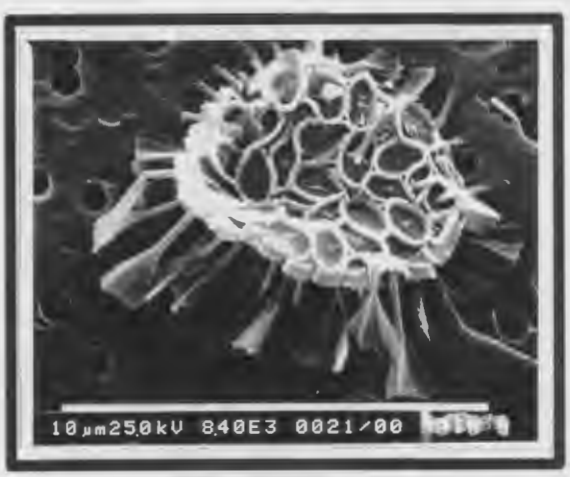

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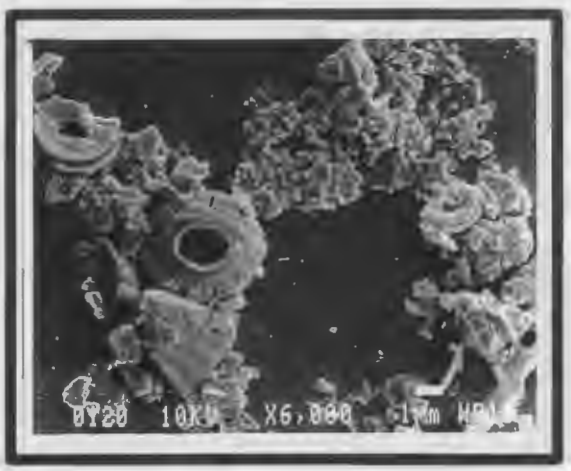

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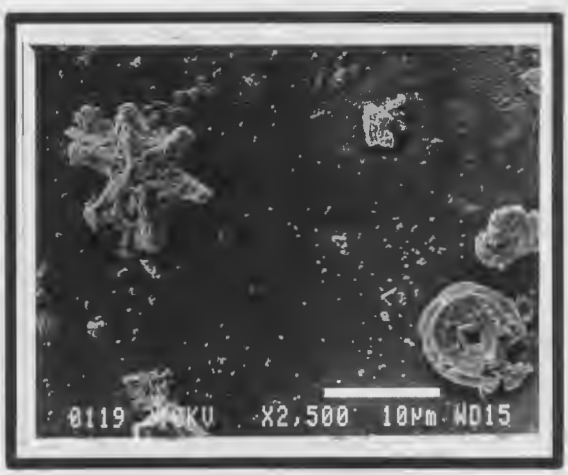

Figure 5

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Figure 8

Appendix A1

Core GC07

CORE	DEPTH IN CORE (cm)	SPECIES (count to ~350)	LM count 1	%	No. of LM fields of view 1mm x 1mm	LM count 2	%	SEM	%	No. of SEM screens 36µm x 46µm
147/GC007	0-1	Coccolithus pelagicus	37	10.22				73	20.73	
Lat. 45°09'S		Calcidiscus leptoporus	196	54.14				235	66.76	
Long. 146°17'E		Helicosphaera carteri	90	24.36				42	11.93	
3307m		Reticulofenestra sp.	4	1.10				0	0	
		Rhabdosphaera clavigera	1	0.27				3	0.85	
		Syracosphaera pulchra	21	5.80				6	1.7	
		Umbilicosphaera sibogae	12	3.31				5	1.42	
		Umbellosphaera tenuis	1	0.27				0	0	
	Total		362		62			352		220
		Emiliania huxleyi	135	38.13				105	29.57	
		Gephyrocapsa muellerae	89	25.14				74	20.84	
		Gephyrocapsa oceanica	17	4.80				2	0.56	
		Gephyrocapsa caribbeanica	27	7.62				6	1.69	
		Gephyrocapsa small	7	1.97				0	0	
		Subordinate	79	22.31				173	48.73	
	Total		354		31			355		138
	13-10	C. pelagicus	8	2.25						
		C. leptoporus	211	59.43						
		H. carteri	76	21.40						
		Oolithus fragilis	4	1.12						
		Reticulofenestra sp.	1	0.28						
		S. pulchra	43	12.11						
		U. sibogae	12	3.38						
	Total		355		127					
		E. huxleyi	210	48.83		211	50.96	170	48.15	
		G. muellerae	108	25.11		98	23.67	68	19.31	
		G. oceanica	6	1.39		9	2.17	11	3.1	
		G. caribbeanica	51	11.86		21	5.07	3	0.84	
		Subordinate	55	12.79		75	18.11	101	28.61	
	Total		430		127	414		353		82
	20-23cm	Acanthoica sp.	2	0.54		0	0			
		C. pelagicus	36	9.80		27	7.47			
		C. leptoporus	192	52.31		195	54.01			
		Calciosolenia murrayi	2	0.54		7	1.93			
		H. carteri	75	20.43		57	15.78			
		O. fragilis	2	0.54		0	0			
		Reticulofenestra sp.	4	1.08		0	0			
		R. clavigera	2	0.54		0	0			
		S. pulchra	33	8.99		62	17.17			
		U. sibogae	19	5.17		13	3.6			
	Total		367		63	361				
		E. huxleyi	178	47.21		216	63.52	183	51.54	
		G. muellerae	73	19.36		77	22.64	54	15.21	
		G. oceanica	15	3.97		23	6.76	4	1.12	
		G. caribbeanica	35	9.28		23	6.76	2	0.56	
		Gephyrocapsa small	1	0.26		1	0.29	0	0	
		Subordinate	75	19.89		0	0	112	31.54	
	Total		377		9	340		355		87
	30-33	Acanthoica sp.	1	0.20		0				
		C. pelagicus	48	13.48		15	4.29			
		C. leptoporus	206	57.80		189	54.15			
		H. carteri	75	21.00		107	30.65			
		O. fragilis	1	0.20		0	0			
		Reticulofenestra sp.	5	1.40		0	0			
		S. pulchra	14	3.90		16	4.58			
		U. sibogae	6	1.68		22	6.3			
	Total		356		150	349				
		E. huxleyi	179	39.86		199	56.05	114	32.02	
		G. muellerae	108	24.05		102	28.73	90	25.28	
		G. oceanica	26	5.79		42	11.83	8	2.24	
		G. caribbeanica	38	8.46		12	3.38	4	1.12	
		Subordinate	98	21.82		0	0	140	39.32	
	Total		449		37	355		356		81
	42-43cm	C. pelagicus	112	30.43						
		C. leptoporus	155	42.11						
		H. carteri	76	20.65						
		Pontosphaera sp.	3	0.81						
		R. clavigera	2	0.54						
		Reticulofenestra sp.	1	0.27						
		S. pulchra	12	3.26						
		U. sibogae	7	1.90						
	Total		368		128					
		E. huxleyi	53	14.44				77	22	
		G. muellerae	194	52.86				99	28.28	
		G. oceanica	38	10.35				14	3.99	
		G. caribbeanica	41	11.17				6	1.71	
		Gephyrocapsa small	6	1.63				0	0	
		Subordinate	35	9.53				155	44.28	
	Total		367					350		140
	45-48	C. pelagicus				72	20.23			
		C. leptoporus				171	48.30			
		C. murrayi				1	0.28			
		H. carteri				67	18.92			
		S. pulchra				41	11.58			
		U. sibogae				2	0.56			
	Total					354				
	45-58	E. huxleyi				73	20.17			
		G. muellerae				126	34.80			
		G. oceanica				19	5.24			
		G. caribbeanica				6	1.65			

Appendix A1
Core GC07

CORE	DEPTH IN CORE (cm)		SPECIES (count to ~350)	LM count 1	%	No. of LM fields of view 1mm x 1mm	LM count 2	%	SEM	%	No. of SEM screens 36µm x 46µm
			Subordinate				138	38.12			
		Total					362				
	51-52		C. pelagicus	85	22.60						
			C. leptoporus	131	34.84						
			C. murrayi	5	1.32						
			Calcidiscus macintyrei	5	1.32						
			Cyclicargolithus floridanus	1	0.26						
			H. carteri	93	24.73						
			R. clavigera	2	0.53						
			S. pulchra	35	9.30						
			U. sibogae	10	2.65						
			U. tenuis	9	2.39						
		Total		376		40					
			E. huxleyi	70	19.83				85	23.6	
			G. muellerae	145	41.07				113	31.38	
			G. oceanica	15	4.24				9	2.5	
			G. caribbeanica	31	8.78				4	1.11	
			Gephyrocapsa small	8	2.26				0	0	
			Subordinate	85	24.00				150	41.66	
		Total		353		10			360		124
	60-63		C. pelagicus				52	15.47			
			C. leptoporus				140	41.66			
			C. murrayi				4	0.29			
			H. carteri				91	27.08			
			S. pulchra				41	12.20			
			U. sibogae				3	0.89			
			U. tenuis				5	1.48			
		Total					336				
			E. huxleyi	43	12.28		75	21.12	121	29.72	
			G. muellerae	86	24.57		144	40.56	144	35.38	
			G. oceanica	3	0.85		9	2.53	3	0.73	
			G. caribbeanica	19	5.42		16	4.5	0	0	
			G.ephyrocapsa small	56	16.00		0	0	0	0	
			Subordinate	143	40.85		111	31.26	142	34.88	
		Total		350			355		407		38
	70-73		C. pelagicus				79	20.46			
			C. leptoporus				150	38.86			
			H. carteri				116	30.05			
			Reticulofenestra sp.				2	0.51			
			R. clavigera				1	0.25			
			S. pulchra				28	7.25			
			U. sibogae				10	2.59			
		Total					386				
			E. huxleyi				81	22.19	68	18.73	
			G. muellerae				107	29.31	111	30.57	
			G. oceanica				9	2.46	1	0.27	
			G. caribbeanica				13	3.56	1	0.27	
			Subordinate				155	42.46	182	50.13	
		Total					365		363		54
	80-83		C. pelagicus				102	30.17			
			C. leptoporus				118	34.91			
			H. carteri				75	22.18			
			S. pulchra				35	10.35			
			U. sibogae				4	1.18			
			U. tenuis				3	0.88			
		Total					337				
			E. huxleyi				50	14.20	57	15.78	
			G. muellerae				196	55.68	160	44.32	
			G. oceanica				10	2.84	5	1.38	
			G. caribbeanica				26	7.39	1	0.27	
			Gephyrocapsa small				0	0.00	14	3.87	
			Subordinate				70	19.88	127	35.18	
		Total					352		361		75
	90-93		C. pelagicus	149	39.41		196	56.97			
			C. leptoporus	143	37.83		87	25.29			
			H. carteri	49	12.96		43	12.50			
			Pontosphaera sp.	5	1.32		2	0.58			
			Reticulofenestra sp.	13	3.43		4	1.16			
			S. pulchra.	9	2.38		9	2.61			
			U. sibogae	5	1.32		2	0.58			
			U. tenuis	2	0.52		1	0.29			
		Total		378		35	344				
			E. huxleyi	79	20.57		49	13.80	52	14.05	
			G. muellerae	199	51.82		168	47.32	179	48.37	
			G. oceanica	7	1.82		4	1.12	3	0.81	
			G. caribbeanica	12	3.12		32	9.01	2	0.54	
			Gephyrocapsa small	6	1.56		0	0.00	0	0	
			Subordinate	85	22.13		102	28.73	144	38.9	
		Total		384		9	355		370		58
	100-103		C. pelagicus	225	61.47		164	46.19			
			C. leptoporus	111	30.32		130	36.61			
			H. carteri	13	3.55		38	10.70			
			O. fragilis	3	0.81		0	0.00			
			Pontosphaera sp.	3	0.81		0	0.00			
			Reticulofenestra sp.	3	0.81		1	0.28			
			S. pulchra	2	0.54		16	4.50			
			U. sibogae	2	0.54		1	0.28			
			U. tenuis	7	1.91		4	1.12			
		Total		366		46	354				

Appendix A1

Core GC07

CORE	DEPTH IN CORE (cm)	SPECIES (count to ~350)	LM count 1	%	No. of LM fields of view 1mm x 1mm	LM count 2	%	SEM	%	No. of SEM screens 36µm x 46µm
		E. huxleyi	71	19.39		63	17.64	34	9.6	
		G. muellerae	175	47.81		168	47.05	148	41.8	
		G. oceanica	1	0.27		63	17.64	35	1.12	
		G. caribbeanica	15	4.09		25	7.00	34	0.28	
		Gephyrocapsa small	6	1.63		0	0.00	0	0	
		Subordinate	88	24.04		38	10.64	172	48.58	
	Total		366		10	357		354		58
	110-113	C. pelagicus	230	62.84						
		C. leptoporus	73	19.94						
		H. carteri	26	7.10						
		H. selli	1	0.27						
		O. fragilis	2	0.54						
		Pontosphaera sp.	2	0.54						
		Reticulofenestra sp.	13	3.55						
		S. pulchra	4	1.09						
		U. sibogae	9	2.45						
		U. tenuis	7	1.91						
	Total		366		26					
		E. huxleyi	59	16.03				37	10.39	
		G. muellerae	195	52.98				159	44.66	
		G. oceanica	5	1.35				0	0	
		G. caribbeanica	27	7.33				0	0	
		Gephyrocapsa small	3	0.81				0	0	
		Subordinate	90	23.74				162	45.5	
	Total							356		120
	120-123	Nil - LGM?								
	130-133	C. pelagicus	57	15.96		71	20.00			
		C. leptoporus	195	54.62		165	46.47			
		H. carteri	52	14.56		97	27.32			
		S. pulchra	31	8.68		10	2.81			
		U. sibogae	19	5.32		12	3.38			
		Reworked sp.	3	0.84		0	0.00			
	Total		357		206	355				
		E. huxleyi	116	32.22		137	39.14	109	31.05	
		G. muellerae	141	39.16		170	48.57	131	37.32	
		G. oceanica	24	6.66		20	5.71	2	0.56	
		G. caribbeanica	28	7.77		23	6.57	0	0	
		Gephyrocapsa small	11	3.05		0	0.00	0	0	
		Subordinate	40	11.11		0	0.00	109	31.05	
	Total		360		17	350		351		72
	140-143	C. pelagicus	249	67.29		227	67.15			
		C. leptoporus	65	17.56		62	18.34			
		H. carteri	40	10.81		47	12.43			
		Pontosphaera sp.	9	2.43		0	0			
		S. pulchra	5	1.35		0	0			
		U. sibogae	2	0.54		2	0.59			
	Total		370		62	338				
		E. huxleyi	94	25.11		79	21.64	105	29.32	
		G. muellerae	132	36.66		23	6.3	128	35.75	
		G. oceanica	19	5.27		20	5.47	0	0	
		G. caribbeanica	43	11.90		104	28.49	0	0	
		Gephyrocapsa small	27	7.50		94	25.75	0	0	
		Subordinate	45	12.50		45	12.32	125	34.91	
	Total		360		18	365		358		86
	150-153	C. pelagicus	186	51.52		152	44.57			
		C. leptoporus	103	28.53		116	34.01			
		C. murrayi	10	0.00		1	0.29			
		H. carteri	57	15.78		66	19.35			
		Pontosphaera sp.	2	0.55		0	0			
		S. pulchra	1	0.27		6	1.75			
		U. sibogae	6	1.66		0	0			
		Reworked sp.	6	1.66		6	0			
	Total		361		198	341				
		E. huxleyi	81	22.75		90	25.56	171	47.23	
		G. muellerae	139	39.00		119	33.8	95	26.24	
		G. oceanica	42	11.79		14	3.97	5	1.38	
		G. caribbeanica	37	10.39		35	9.94	0	0	
		Gephyrocapsa small	22	6.17		82	23.29	0	0	
		Subordinate	35	9.83		12	3.4	91	25.13	
	Total		356		23	352		362		51
	160-163	C. pelagicus	203	56.23		230	64.78			
		C. leptoporus	83	22.99		69	19.43			
		C. macintyrei	2	0.55		0	0			
		H. carteri	40	11.08		40	11.26			
		Pontosphaera sp.	8	2.21		9	2.53			
		R. clavigera	1	0.27		0	0			
		S. pulchra	16	4.43		5	1.4			
		U. sibogae	8	2.21		2	0.56			
	Total		361		187	355				
		E. huxleyi	102	28.89		85	23.54	65	18.25	
		G. muellerae	122	34.56		164	45.42	184	51.68	
		G. oceanica	21	5.94		10	2.77	1	0.28	
		G. caribbeanica	62	17.56		33	9.14	14	3.93	
		Gephyrocapsa small	16	4.53		34	9.41	0	0	
		Subordinate	30	8.49		35	9.69	92	25.84	
	Total		353		15	361		356	60	
	170-173	C. pelagicus	230	63.36		251	65.02			
		C. leptoporus	54	14.87		77	19.94			
		H. carteri	57	15.70		33	8.54			

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Core GC07

CORE	DEPTH IN CORE (cm)	SPECIES (count to ~350)	LM count 1	%	No. of LM fields of view 1mm x 1mm	LM count 2	%	SEM	%	No. of SEM screens 36µm x 46µm
		O. fragilis	0	0.00		2	0.51			
		Pontosphaera sp.	8	2.20		16	4.14			
		R. clavigera	2	0.55		1	0.25			
		S. pulchra	6	1.65		6	1.55			
		U. sibogae	6	1.65		0	0			
		U. tenuis	3	0.82		0	0			
	Total		363		126	386				
		E. huxleyi	63	17.79		62	17.27	63	16.32	
		G. muellerae	128	36.15		149	41.5	195	50.5	
		G. oceanica	39	11.00		12	3.34	0	0	
		G. caribbeanica	79	22.31		73	20.33	19	4.92	
		Gephyrocapsa small	20	5.64		46	12.81	0	0	
		Subordinate	25	7.06		17	4.73	109	28.23	
	Total		354		20	359		386		58
	180-183	C. pelagicus	146	40.78						
		C. leptoporus	136	37.98						
		H. carteri	57	15.92						
		S. pulchra	7	1.95						
		U. tenuis	2	0.55						
		U. sibogae	7	1.95						
		Reworked sp.	3	0.83						
	Total		358		111					
		E. huxleyi	48	12.59				63	17.79	
		G. muellerae	164	43.04				216	61	
		G. oceanica	59	15.50				9	2.54	
		G. caribbeanica	69	18.11				25	7.06	
		Gephyrocapsa small	17	4.46				0	0	
		Subordinate	24	6.29				41	11.58	
	Total		381		8			354	55	
	190-193	C. pelagicus	177	50.28						
		C. leptoporus	111	31.53						
		H. carteri	49	13.92						
		Pontosphaera sp.	2	0.56						
		R. clavigera	3	0.85						
		S. pulchra	6	1.70						
		U. sibogae	4	1.13						
	Total		352		101					
		E. huxleyi	65	17.95				91	24.93	
		G. muellerae	156	43.09				210	57.53	
		G. oceanica	14	3.86				12	3.28	
		G. caribbeanica	73	20.16				0	0	
		Gephyrocapsa small	6	1.65				0	0	
		Subordinate	48	13.00				52	14.24	
	Total		362		12			365		39
	200-203	C. pelagicus				150	42.85			
		C. leptoporus				129	36.85			
		C. murrayi				1	0.28			
		C. macintyrei				4	1.14			
		H. carteri				57	16.28			
		R. clavigera				1	0.28			
		S. pulchra				7	2.00			
		Reworked sp.				1	0.29			
	Total					350				
		E. huxleyi				81	22.80	27	7.43	
		G. muellerae				157	44.20	223	61.43	
		G. oceanica				7	1.97	8	1.92	
		G. caribbeanica				54	15.21	17	0.46	
		Subordinate				56	15.77	90	24.79	
	Total					355		363		34
	210-213	C. pelagicus	195	52.84						
		C. leptoporus	94	25.47						
		H. carteri	48	13.00						
		R. clavigera	2	0.54						
		S. pulchra	14	3.79						
		U. tenuis	1	0.27						
		U. sibogae	8	2.16						
		Reworked sp.	7	1.89						
	Total		369		132					
		E. huxleyi	53	14.44				13	3.43	
		G. muellerae	194	52.86				280	74.07	
		G. oceanica	38	10.35				4	1.05	
		G. caribbeanica	41	11.17				1	0.26	
		Gephyrocapsa small	6	1.63				0	0	
		Subordinate	35	9.53				80	21.16	
	Total		367		36			378		59
	230-233	C. pelagicus	184	50.82						
		C. leptoporus	93	25.69						
		H. carteri	56	15.46						
		Pontosphaera sp.	4	1.10						
		S. pulchra	9	2.48						
		U. sibogae	8	2.20						
		Reworked sp.	8	2.20						
	Total		362		188					
		E. huxleyi	52	14.68				38	10.52	
		G. muellerae	196	55.36				253	70.08	
		G. oceanica	19	5.36				10	2.76	
		G. caribbeanica	34	9.60				17	4.7	
		Gephyrocapsa small	13	3.67				0	0	
		Subordinate	40	11.29				43	21.16	
	Total		354		18			361		73

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CORE	DEPTH IN CORE (cm)		SPECIES (count to ~350)	LM count 1	%	No. of LM fields of view 1mm x 1mm	LM count 2	%	SEM	%	No. of SEM screens 36µm x 46µm
	250-253		C. pelagicus	286	73.14						
			C. leptoporus	38	9.71						
			C. macintyrei	10	2.55						
			C. floridanus	14	3.58						
			Discoaster sp.	1	0.25						
			H. carteri	30	7.67						
			O. fragilis	2	0.51						
			Pontosphaera sp.	2	0.51						
			Reticulofenstra sp. small	3	0.76						
			S. pulchra	4	1.02						
			U. tenuis	1	0.25						
		Total		391							
			E. huxleyi	67	18.25				36	9.89	
			G. muellerae	225	61.30				239	65.65	
			G. oceanica	12	3.26				8	2.19	
			G. caribbeanica	12	3.26				15	4.12	
			Gephyrocapsa small	8	2.17				0	0	
			Subordinate	26	7.08				66	18.13	
		Total		367		20			364		83
	270-273		C. pelagicus	189	53.69						
			C. leptoporus	44	12.15						
			C. murrayi	1	0.28						
			C. macintyrei	25	7.10						
			C. floridanus	45	12.78						
			Discoaster sp.	2	0.56						
			H. carteri	35	9.94						
			O. fragilis	1	0.28						
			Pontosphaera sp.	5	1.42						
			Reticulofenstra sp.	3	0.85						
			S. pulchra	7	1.98						
			U. sibogae	1	0.28						
		Total		352		101					
			Ascidian spicules	2							
			E. huxleyi	31	8.58				36	10.22	
			G. muellerae	162	44.87				168	47.72	
			G. oceanica	4	1.10				7	1.98	
			G. caribbeanica	85	23.54				12	3.4	
			Gephyrocapsa small	13	3.60				8	2.27	
			Subordinate	66	18.28				121	34.37	
		Total		361		15			352		
	290-293		C. pelagicus	291	71.32						
			C. leptoporus	40	9.80						
			C. macintyrei	3	0.73						
			C. floridanus	3	0.73						
			H. carteri	33	8.08						
			Pontosphaera sp.	2	0.49						
			R. clavigera	2	0.49						
			S. pulchra	22	5.39						
			U. sibogae	9	2.20						
			U. tenuis	3	0.73						
		Total		408		141					
			E. huxleyi	57	15.78				45	12.74	
			G. muellerae	173	47.92				217	61.47	
			G. oceanica	35	9.69				3	0.84	
			G. caribbeanica	39	10.80				19	5.38	
			Subordinate	58	16.06				69	19.54	
		Total		361		21			353		97
	310-313		C. pelagicus	321	87.46						
			C. leptoporus	26	7.08						
			Ceratolithus cristatus	1	0.27						
			H. carteri	8	2.17						
			Pontosphaera sp.	1	0.27						
			Reticulofenestra sp. med. closed	1	0.27						
			Reticulofenestra sp. med. open	2	0.54						
			R. gelida	2	0.54						
			R. pseudoumbilica	3	0.81						
			S. pulchra	2	0.54						
		Total		367		39					
			E. huxleyi	34	9.68				51	14.36	
			G. muellerae	201	57.26				193	54.36	
			G. oceanica	1	0.28				3	0.84	
			G. caribbeanica	17	4.84				21	5.91	
			Gephyrocapsa small	71	20.22						
			Subordinate	28	7.97				91	25.63	
		Total		351		6			355		61
	330-333		C. pelagicus	273	73.19						
			C. leptoporus	54	17.47						
			C. floridanus	2	0.53						
			H. carteri	22	5.89						
			Pontosphaera sp.	3	0.8						
			P. lacunosa	1	0.26						
			R. clavigera	1	0.26						
			Reticulofenestra sp. med. closed	5	1.34						
			Reticulofenestra sp. med. open	2	0.53						
			R. gelida	2	0.53						
			R. pseudoumbilica	1	0.26						
			S. pulchra	2	0.53						
		Total		373		70					
			E. huxleyi	44	12.50				39	10.54	
			G. muellerae	218	61.93				231	62.43	
			G. oceanica	4	1.13				13	10.81	
			G. caribbeanica	34	9.65				40	3.51	

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CORE	DEPTH IN CORE (cm)		SPECIES (count to ~350)	LM count 1	%	No. of LM fields of view 1mm x 1mm	LM count 2	%	SEM	%	No. of SEM screens 36µm x 46µm
			Gephyrocapsa small	39	11.07				3	0.81	
			Subordinate	16	4.54				43	11.62	
		Total		352		7			370		64
	350-353		C. pelagicus	272	75.13		171	48.57			
			C. leptoporus	44	9.39		72	20.45			
			C. floridanus	5	1.38		6	1.70			
			H. carteri	27	7.45		83	23.57			
			Reticulofenestra sp. small closed	1	0.27		9	2.55			
			Reticulofenestra sp. med. closed	1	0.27		341				
			Reticulofenestra sp. med. open	4	1.10						
			R. gelida	1	0.27						
			R. pseudoumbilica	2	0.55						
			S. pulchra	4	1.10		11	3.12			
		Total		362		74					
			E. huxleyi	59	16.52		39	11.27	35	9.91	
			G. muellerae	221	61.90		241	69.65	264	74.78	
			G. oceanica	5	1.40		4	1.15	5	1.4	
			G. caribbeanica	11	0.28		5	1.44	9	2.54	
			Gephyrocapsa small	25	7.00						
			Subordinate	36	10.08		57	16.47	40	11.33	
		Total		357		6	346		353		46
	370-373		C. pelagicus	175	46.29						
			C. leptoporus	109	28.83						
			C. floridanus	20	5.29						
			H. carteri	65	17.19						
			Pontosphaera sp.	1	0.26						
			Reticulofenestra sp. med. closed	1	0.26						
			R. gelida	2	0.52						
			S. pulchra	3	0.79						
			U. tenuis	2	0.52						
		Total		378		50					
			E. huxleyi	69	18.85						
			G. muellerae	200	54.64						
			G. oceanica	5	1.35						
			G. caribbeanica	10	2.73						
			Gephyrocapsa small	26	7.10						
			Subordinate	61	16.66						
		Total		366		5					
	390-393		C. pelagicus	121	29.36						
			C. leptoporus	164	39.80						
			C. floridanus	7	1.69						
			H. carteri	79	19.17						
			Pontosphaera sp.	3	0.72						
			Reticulofenestra small closed	1	0.24						
			Reticulofenestra med. closed	1	0.24						
			Reticulofenestra med. open	2	0.48						
			R. gelida	2	0.48						
			R. pseudoumbilica	2	0.48						
			S. pulchra	16	3.88						
			U. tenuis	4	0.97						
			U. sibogae	10	2.42						
		Total		412		43					
			E. huxleyi	44	12.50						
			G. muellerae	129	36.64						
			G. oceanica	1	0.28						
			G. caribbeanica	13	3.69						
			Gephyrocapsa small	121	34.37						
			Subordinate	44	12.50						
		Total		352		9					
	410-413		C. pelagicus	121	31.18						
			C. leptoporus	113	29.12						
			C. floridanus	16	4.12						
			H. carteri	110	28.34						
			Pontosphaera sp.	4	1.03						
			Reticulofenestra sp. small closed	4	1.03						
			Reticulofenestra sp. med. open	3	0.77						
			R. gelida	4	1.03						
			R. pseudoumbilica	1	0.25						
			S. pulchra	3	0.77						
			U. tenuis	2	0.51						
			U. sibogae	6	1.54						
		Total		388		82					
			E. huxleyi	48	13.59						
			G. muellerae	173	49.00						
			G. oceanica	3	0.84						
			G. caribbeanica	16	4.53						
			Gephyrocapsa small	74	20.96						
			Subordinate	39	11.04						
		Total		353		9					
	430-433		C. pelagicus	110	29.41						
			C. leptoporus	99	26.47						
			C. floridanus	5	1.33						
			H. carteri	144	38.49						
			Reticulofenestra sp. small closed	6	1.60						
			R. gelida	1	0.26						
			R. pseudoumbilica	3	0.80						
			S. pulchra	2	0.53						
			U. tenuis	1	0.26						
			U. sibogae	3	0.80						
		Total		374		42					
			E. huxleyi	38	10.46						

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CORE	DEPTH IN CORE (cm)	SPECIES (count to ~350)	LM count 1	%	No. of LM fields of view 1mm x 1mm	LM count 2	%	SEM	%	No. of SEM screens 36µm x 46µm
		G. muellerae	154	42.42						
		G. oceanica	2	0.54						
		G. caribbeanica	18	4.95						
		Gephyrocapsa small	10	27.54						
		Subordinate	51	14.04						
	Total		363		7					
	450-453	C. pelagicus	184	49.06						
		C. leptoporus	97	25.86						
		C. floridanus	11	2.93						
		H. carteri	68	18.13						
		Reticulofenestra sp. small closed	3	0.80						
		R. pseudoumbilica	2	0.53						
		S. pulchra	4	1.06						
		U. tenuis	1	0.26						
		U. sibogae	4	1.06						
	Total		375		52					
		E. huxleyi	39	11.01						
		G. muellerae	185	52.25						
		G. oceanica	4	1.12						
		G. caribbeanica	20	5.64						
		Gephyrocapsa small	61	17.23						
		Subordinate	45	12.71						
	Total									
	470-473	Acanthoica sp.	1	0.26						
		C. pelagicus	131	35.02						
		C. leptoporus	118	31.55						
		C. murrayi	3	0.80						
		C. floridanus	17	4.54						
		H. carteri	83	22.19						
		O. fragilis	4	1.06						
		P. lacunosa	3	0.80						
		R. clavigera	1	0.26						
		Reticulofenestra sp. small closed	6	1.60						
		R. psuedoumbilica	1	0.26						
		S. pulchra	7	1.87						
		U. tenuis	1	0.26						
		U. sibogae	3	0.80						
	Total		374		37					
		E. huxleyi	43	11.90						
		G. muellerae	174	48.19						
		G. oceanica	2	0.54						
		G. caribbeanica	8	2.21						
		Gephyrocapsa small	95	26.31						
		Subordinate	39	10.80						
	Total		361		5					
	490-493	Acanthoica sp.	1	0.26						
		C. pelagicus	154	40.63						
		C. leptoporus	112	29.55						
		C. floridanus	19	5.01						
		H. carteri	81	21.37						
		Reticulofenestra sp. small closed	1	0.26						
		Reticulofenestra sp. med. closed	1	0.26						
		R. pseudoumbilica	1	0.26						
		S. pulchra	7	1.84						
		U. sibogae	2	0.52						
	Total		379		33					
		E. huxleyi	44	12.22						
		G. muellerae	194	53.88						
		G. oceanica	5	1.38						
		G. caribbeanica	30	8.33						
		Gephyrocapsa small	52	14.44						
		Subordinate	45	12.50						
	Total		360		6					
	510-513	Acanthoica sp.	3	0.79						
		C. pelagicus	56	14.77						
		C. leptoporus	129	34.03						
		C. floridanus	19	5.01						
		H. carteri	143	37.73						
		H. sellii	3	0.79						
		Pontosphaera sp.	2	0.52						
		P. lacunosa	4	1.05						
		Reticulofenestra sp. small closed	2	0.52						
		Reticulofenestra sp. med. closed	2	0.52						
		R. pseudoumbilica	3	0.79						
		S. pulchra	2	0.52						
		U. tenuis	4	1.05						
		U. sibogae	7	1.84						
	Total		379		51					
		E. huxleyi	32	8.60						
		G. muellerae	170	47.09						
		G. oceanica	10	2.77						
		G. caribbeanica	8	2.21						
		Gephyrocapsa small	67	18.55						
		Subordinate	75	20.77						
	Total		361		13					

Appendix A2 - Data for all surface sediment samples
(listed in order related to latitude and position of oceanic fronts.)

Core Number	Species Identified	Light Microscope Count One (Count Two)	% species	Number of Screens 1mm X 1mm	Electron Microscope	% species	Number of Screens 35µm X 46µm
147/GC032	Emiliania huxleyi	22	6.14		62	17.61	
Lat. 43°57.93S	Gephyrocapsa muellerae	141	39.38		120	34.09	
2650m	Gephyrocapsa oceanica <5µm	18	5.02		8	2.27	
NOT HOLOCENE	Gephyrocapsa oceanica >5µm	2	0.55		0	0	
	Gephyrocapsa caribbeanica	19	5.3		0	0	
	small Gephyrocapsa spp	31	8.65		0	0	
	Subordinate	125	34.91		163	46.3	
Total		358		19	352		122
147/GC004	E. huxleyi	(70)68	19.2		153	43.46	
Lat. 44°05.99S	G. muellerae	(154)120	33.89		67	19.03	
2981m	G. oceanica <5µm	(4)4	1.12		3	0.85	
NOT HOLOCENE	G. oceanica >5µm	1	0.28		0	0	
	G. caribbeanica	(24)24	6.77		0	0	
	small Gephyrocapsa spp	(11)32	9.03		0	0	
	Subordinate	(96)106	29.94		131	37.21	
Total		(359)354			352		57
147/GC005	E. huxleyi	92	26.21		182	50.98	
Lat.44°03.99S	G. muellerae	141	40.17		78	21.84	
2334m	G. oceanica <5µm	13	3.7		7	1.96	
NOT HOLOCENE	G. oceanica >5µm	5	1.42		2	0	
	G. caribbeanica	29	8.26		0	0	
	small Gephyrocapsa spp	68	19.37		0	0	
	Subordinate	99	28.2		90	25.21	
Total		351		50	357		47
147/GC001	E. huxleyi	12	3.2		38	10.73	
Lat. 44°10.30S	G. muellerae	120	32.08		104	29.37	
4238m	G. oceanica <5µm	11	2.94		4	1.13	
NOT HOLOCENE	G. oceanica >5µm	2	0.53		0	0	
	G. caribbeanica	7	1.87		0	0	
	small Gephyrocapsa spp	27	7.21		0	0	
	Subordinate	195	52.13		211	59.77	
Total		374		32	354		65
147/GC006	E. huxleyi	48	13.25		140	39.66	
Lat.44°31.51S	G. muellerae	114	31.49		72	20.39	
2609m	G. oceanica <5µm	11	3.03		4	1.13	
NOT HOLOCENE	G. oceanica >5µm	4	1.1		3	0.8	
	G. caribbeanica	28	7.73		0	0	
	small Gephyrocapsa spp	30	8.28		0	0	
	Subordinate	127	35.08		137	38.81	
Total		362		20	353		56
147/GC031	E. huxleyi	27	7.21		91	25.41	
Lat. 44°32.79S	G. muellerae	178	47.59		85	23.74	
3440m	G. oceanica <5µm	14	3.74		10	2.79	
NOT HOLOCENE	G. oceanica>5µm	0	0		2	0.55	
	G. caribbeanica	30	8.02		0	0	
	small Gephyrocapsa spp	34	9.09		0	0	
	Subordinate	93	24.86		175	48.88	
Total		374		15	358		57
MD972112	Emiliania huxleyi	29	8.26		44	12.39	
Lat. 41°15.70S	G. muellerae	128	34.46		90	27.88	
3975m	G. oceanica <5µm	53	15.09		20	5.63	
NOT HOLOCENE	G. oceanica >5µm	8	2.27		0	0	
	G. caribbeanica	15	4.27		0	0	
	small Gephyrocapsa spp	21	5.98		0	0	
	Subordinate	97	27.63		197	55.49	
Total		351		9	355		62
147/GC034	E. huxleyi	35	9.58				
45°06.00S	G. muellerae	100	27.39				
4202m	G. oceanica <5µm	25	6.84				
NOT HOLOCENE	G. caribbeanica	8	2.19				
	Subordinate	198	54.24	27			
Total		365					
MD972106	E. huxleyi	99	27.73		173	48.59	
Lat. 45°09.69S	G. muellerae	124	34.73		50	14.04	
3310m	G. oceanica <5µm	2	0.56		8	2.24	
NOT HOLOCENE	G. caribbeanica	38	10.64		0	0	
	small Gephyrocapsa spp	12	3.36		0	0	
	Subordinate	82	22.96		125	35.11	
Total		357		8	356		92
147/GC007	E. huxleyi	135	38.13		105	29.57	
Lat. 45°09.52S	G. muellerae	89	25.14		74	20.84	
3307m	G. oceanica <5µm	17	4.8		2	0.56	
HOLOCENE	G. oceanica >5µm	0	0		0	0	
	G. caribbeanica	27	7.62		6	1.69	
	small Gephyrocapsa spp	7	1.97		0	0	
	Subordinate	79	22.31		173	48.73	
Total		354		31	355		138
	Calcidiscus pelagicus	8	2.25		73	20.73	
	Coccolithus leptoporus	211	59.43		235	66.76	
	Helicospheara carteri	76	21.4		42	11.93	
	Oolithus fragilis	4	1.12				
	Reticulofenestra sp.	1	0.28		3	0.85	

Appendix A2 - Data for all surface sediment samples
(listed in order related to latitude and position of oceanic fronts.)

Core Number	Species Identified	Light Microscope Count One (Count Two)	% species	Number of Screens 1mm X 1mm	Electron Microscope	% species	Number of Screens 35µm X 46µm
	Syracosphaera pulchra	43	12.11		6	1.7	
	Umbilicosphaera sibogae	12	3.38		5	1.42	
Total		355		127	352		220
147/GC035	E. huxleyi	7	2.00		0	0.00	
Lat. 45°44.00S	G. muellerae	154	44.12		105	29.91	
2720m	G. oceanica	8	2.29		192	54.7	
NOT HOLOCENE	G. caribbeanica	112	32.09		3	0.85	
	small Geyphrocapsa spp	12	3.43				
	Subordinate	56	16.04		53	15.09	
Total		349		16	351		76
147/GC011	E. huxleyi	64	17.92		104	29.54	
Lat.45°44.02S	G. muellerae	167	46.77		132	37.5	
2387m	G. oceanica <5µm	2	0.56		3	0.85	
NOT HOLOCENE	G. caribbeanica	5	1.4		0	0	
	small Gephyrocapsa spp	40	11.2		0	0	
	Subordinate	79	22.12		114	32.38	
Total		357		62	352		52
SUBTROPICAL FRONT							
MD972113	E. huxleyi	42	11.66		122	30.19	
Lat. 42°00.80S	G. muellerae	179	49.72		71	17.57	
2936m	G. oceanica <5µm	6	1.66		20	5.63	
NOT HOLOCENE	G. oceanica >5µm	16	4.44		0	0	
	G. caribbeanica	39	10.83		0	0	
	small Gephyrocapsa spp	25	6.94		0	0	
	Subordinate	53	14.72		194	48.01	
Total		360		9	404		73
MD972115	E. huxleyi	24	6.64		138	37.19	
Lat. 43°10.84S	G. muellerae	162	44.87		79	21.29	
2160m	G. oceanica <5µm	2	0.55		20	5.39	
NOT HOLOCENE	G. oceanica >5µm	30	8.31		0	0	
	G. caribbeanica	33	9.14		0	0	
	small Gephyrocapsa spp	16	4.43		0	0	
	Subordinate	94	26.03		139	37.46	
Total		361		7	371		45
147/GC028	E. huxleyi	41	11.64		71	19.83	
Lat. 46°03.48S	G. muellerae	80	22.72		112	31.28	
3065m	G. oceanica <5µm	5	1.42		4	1.11	
NOT HOLOCENE	G. caribbeanica	43	12.21		9	2.51	
	small Gephyrocapsa spp	55	15.62		0	0	
	Subordinate	128	36.36		167	46.64	
Total		352		16	358		90
147/GC030	E. huxleyi	56	15.46		111	31	
Lat. 46°09.99S	G. muellerae	117	32.32		82	22.9	
2968m	G. oceanica <5µm	11	3.03		9	2.51	
NOT HOLOCENE	G. caribbeanica	38	10.49		0	0	
	small Gephyrocapsa spp	37	10.22		0	0	
	Subordinate	104	28.72		158	44.13	
Total		362		25	358		119
147/GC013	E. huxleyi	42	11.6		122	30.19	
Lat.46°10.01S	G. muellerae	179	49.72		71	17.57	
4452m	G. oceanica <5µm	6	1.66		20	5.63	
NOT HOLOCENE	G. oceanica >5µm	16	4.44		0	0	
very few coccoliths	G. caribbeanica	39	10.83		0	0	
	small Gephyrocapsa spp	25	6.94		0	0	
	Subordinate	53	14.72		194	48.01	
		360			404		
147/GC014	E. huxleyi	65	18.3		108	30.42	
Lat. 46°26.98S	G. muellerae	108	30.42		52	14.64	
3360m	G. oceanica <5µm	1	0.28		5	1.4	
NOT HOLOCENE	G. oceanica >5µm	3	0.84		0	0	
	G. caribbeanica	13	3.66		0	0	
	small Gephyrocapsa spp	7	1.97		0	0	
	Subordinate	157	44.22		193	54.36	
Total		355		13	355		42
147/GC016	E. huxleyi	97	22.04		72	20.28	
Lat.46°47.99S	G. muellerae	303	68.86		229	64.5	
3523m	G. oceanica <5µm	0	0		2	0.56	
NOT HOLOCENE	G. caribbeanica	2	0.45		0	0	
	small Gephyrocapsa spp	7	1.59		0	0	
	Subordinate	30	6.81		52	14.64	
Total		440		19	355		30
MD_88778	Emiliania huxleyi	45	12.56				
Lat. 46°57.59S	G. muellerae	112	31.28				
3540m	G. oceanica	5	1.39				
NOT HOLOCENE	G. caribbeanica	77	21.50				
	small Gephyrocapsa spp	57	15.92				
	Subordinate species	64	17.87				
Total		358		13.00			
SUBTROPICAL FRONT							

Appendix A2 - Data for all surface sediment samples
(listed in order related to latitude and position of oceanic fronts.)

Core Number	Species Identified	Light Microscope Count One (Count Two)	% species	Number of Screens 1mm X 1mm	Electron Microscope	% species	Number of Screens 35µm X 46µm
MD972118	E. huxleyi	148	42.04		138	38.76	
Lat. 45°07.01S	G. muellerae	88	25		27	7.58	
2690m	G. oceanica < 5µm	0	0		13	3.65	
HOLOCENE	G. caribbeanica	9	2.55		0	0	
	small Gephyrocapsa spp	11	3.12		0	0	
	Subordinate	95	26.98		186	52.24	
Total		352		9	356		44
	C. pelagicus	12	3.23			20	5.3
	C. leptoporus	307	82.74			318	84.35
	H. carteri	29	7.81			20	5.3
	Rhabdosphaera clavigera	0	0			4	1.06
	Reticulofenestra gelida-large closed	1	0.26			0	0
	Reticulofenestra sp. medium -open	1	0.26			0	0
	Reticulofenestra sp. medium - closed	1	0.26			0	0
	Reticulofenestra producta - small closed	1	0.26			0	0
	S. pulchra	3	0.8			5	1.32
	U. sibogae	5	1.34			6	1.59
	Umbellosphaera tenuis	12	3.23			4	1.06
Total		372		16		377	
MD972108	E. huxleyi	131	35.59		182	51.85	
Lat. 48°29.28S	G. muellerae	116	31.52		29	8.26	
2140m	G. oceanica <5µm				5	1.42	
HOLOCENE	G. caribbeanica	14	3.8		0	0	
	small Gephyrocapsa spp	14	3.8		0	0	
	Subordinate	92	25		137	39.03	
Total		368		12	351		83
	C. pelagicus	8	2.25		0	0	
	C. leptoporus	275	77.68		315	88.23	
	H. carteri	33	9.32		37	10.36	
	R. clavigera	1	0.28		1	0.28	
	S. pulchra	11	3.1		3	0.84	
	U. sibogae	7	1.97		2	0.56	
	U. tenuis	19	5.36		0	0	
Total		354		17	357		139
KR 8807	E. huxleyi	63	17.26				
Lat. 47°08.87S	G. muellerae	117	32.05				
2890m	G. oceanica	30	8.20				
NOT HOLOCENE	G. caribbeanica	24	6.57				
	Subordinate	132	36.16				
Total		365		34.00			
147/GR001	E huxleyi	82	22.58				
Lat. 47°39.06'S	G. muellerae	122	33.6				
1311m	G. oceanica <5µm	2	0.55				
NOT HOLOCENE	G. caribbeanica	28	7.71				
	small Gephyrocapsa spp	9	2.47				
	Subordinate	120	33.05				
Total		363		13			
147/GC017	E. huxleyi	58	15.97		101	28.29	
Lat. 47°45.04S	G. muellerae	122	33.6		52	14.56	
3001m	G. oceanica <5µm	6	1.65		0	0	
NOT HOLOCENE	G. oceanica >5µm	4	1.1		2	0.56	
	G. caribbeanica	23	6.33		13	3.64	
	small Gephyrocapsa spp	10	2.75		0	0	
	Subordinate	142	39.11		193	54.06	
Total		363		15	357		104
MD972107	E. huxleyi	105	29.66		158	44.88	
Lat. 47°42.70S	G. muellerae	137	38.7		42	11.93	
2950m	G. oceanica <5µm				7	1.98	
NOT HOLOCENE	G. caribbeanica	20	5.64		0	0	
	small Gephyrocapsa spp	10	2.82		0	0	
	Subordinate	83	23.44		146	41.47	
Total		354		6	352		54
MD 88779	E. huxleyi	78	21.19				
Lat. 47°50.69S	G. muellerae	182	49.45				
2260m	G. oceanica	3	0.81				
NOT HOLOCENE	G. caribbeanica	65	17.66				
	small Gephyrocapsa spp	20	5.43				
	Subordinate	20	5.43				
Total		368		18.00			
147/GC020	E. huxleyi	48	13.55				
Lat.48°39.03S	G. muellerae	100	28.24				
3300m	G. oceanica <5µm	7	1.97				
NOT HOLOCENE	G. caribbeanica	56	15.81				
	small Gephyrocapsa spp	80	22.59				
	Subordinate	64	18.07				
Total		354		21			
147/GC021	E. huxleyi	23	6.47		48	13.18	
Lat. 49°00.16S	G. muellerae	37	10.42		54	14.83	
4132m	G. oceanica <5m	4	1.12		0	0	
NOT HOLOCENE	G. caribbeanica	14	3.94		0	0	
	small Gephyrocapsa spp	25	7.04		0	0	
	Subordinate	248	69.85		265	72.8	
Total		355		34	364		64

Appendix A2 - Data for all surface sediment samples
(listed in order related to latitude and position of oceanic fronts.)

Core Number	Species Identified	Light Microscope Count One (Count Two)	% species	Number of Screens 1mm X 1mm	Electron Microscope	% species	Number of Screens 35µm X 46µm
MD 88781	E. huxleyi	47	13.27		97	27.71	
Lat. 49°07.52S	G. muellerae	150	42.37		141	40.28	
2490m	G. caribbeanica	119	33.61		33	9.42	
NOT HOLOCENE	small Gephyrocapsa spp	0	0.00		27	7.71	
	Subordinate	38	10.73		43	12.28	
Total		354			350		67
KR 8808	E. huxleyi	60	16.80		122	33.15	
Lat. 49°15.69S	G. muellerae	37	10.36		65	17.66	
3885m	G. oceanica	17	4.76		2	0.54	
HOLOCENE	G. caribbeanica	17	4.76				
	small Gephyrocapsa spp	9	2.52		3	0.81	
	Subordinate	218	61.06		174	47.28	
Total		357		44.00	368		41
	C. pelagicus	89	24.38				
	C. leptoporus	159	43.56				
	Calcidiscus macintyrei	6	1.64				
	H. carteri	88	24.10				
	O. fragilis	1	0.27				
	R. gelida - large closed	3	0.82				
	R. producta - small closed	2	0.54				
	Reticulofenestra sp. - medium open	1	0.27				
	S. pulchra	3	0.82				
	U. tenuis	1	0.27				
	U. sibogae	13	3.56				
Total		365		78.00			
MD 88780	E. huxleyi	55	15.40		83	23.44	
Lat. 49°16.44S	G. muellerae	140	39.21		199	56.21	
3890m	G. oceanica	9	2.52		4	1.12	
NOT HOLOCENE	G. caribbeanica	79	22.12		20	5.64	
	small Gephyrocapsa spp	51	14.28		6	1.69	
	Subordinate	24	6.72		43	12.14	
Total		357		12.00	354		61
MD 88782							
Lat. 50°35.52S							
4350m							
Very few coccoliths.							
KR 8809							
Lat. 50°35.60S							
4350m							
Coccoliths are very rare and re-worked.							
MD 88777	E. huxleyi	46	13.10		57	16.05	
Lat. 49°14.90S	G. muellerae	110	31.33		95	26.76	
3250m	G. oceanica	8	2.27		4	1.12	
NOT HOLOCENE	G. caribbeanica	11	3.13		2	0.56	
	small Gephyrocapsa spp	26	7.40		0	0.00	
	Subordinate	150	42.73		200	56.33	
Total		351		55.00	355		96
MD972110	E. huxleyi	136	38.09		169	47.87	
lat. 48°25.74S	G. muellerae	82	22.96		46	13.03	
1345m	G. oceanica <5µm				5	1.41	
HOLOCENE	G. caribbeanica	6	1.68		0	0	
	small Gephyrocapsa spp	11	3.08		0	0	
	Subordinate	121	33.89		134	37.96	
Total		357		8	353		66
	C. pelagicus	8	2.14		0	0	
	C. leptoporus	310	83.1		308	87.74	
	H. carteri	23	6.16		26	7.4	
	R. gelida - large closed	2	0.53		0	0	
	Reticulofenestra sp. - medium closed	3	0.8		0	0	
	S. pulchra	11	2.94		7	1.99	
	U. sibogae	6	1.6		8	2.27	
	U. tenuis	10	2.68		2	0.56	
Total		373		13	351		137
SUBANTARCTIC FRONT							
MD 88783	E. huxleyi	112	31.11		238	66.66	
Lat. 52°23.57S	G. muellerae	80	22.22		22	6.16	
3170m	G. oceanica	4	1.10		2	0.56	
HOLOCENE	G. caribbeanica	16	4.44		0	0.00	
	small Gephyrocapsa spp	75	20.83		0	0.00	
	Subordinate	71	19.72		101	28.29	
Total		360		13.00	357		241
	C. pelagicus	7	1.86				
	C. leptoporus	277	73.86				
	C. macintyrei	15	4.00				
	H. carteri	43	11.34				
	R. gelida - large open	3	0.80				
	Reticulofenestra sp. - medium closed	1	0.26				
	R. producta - small closed	7	1.86				
	S. pulchra	13	3.43				
	U. sibogae	9	2.40				
Total		375		51.00			
POLAR FRONT							

Appendix A2 - Data for all surface sediment samples
(listed in order related to latitude and position of oceanic fronts.)

Core Number	Species Identified	Light Microscope Count One (Count Two)	% species	Number of Screens 1mm X 1mm	Electron Microscope	% species	Number of Screens 35µm X 46µm
KR 8810	E. huxleyi	249	69.35		223	68.61	
Lat. 54°11.16S	G. muellerae	58	16.15		48	14.76	
2785m	G. caribbeanica	2	0.55		0	0.00	
HOLOCENE	Subordinate	50	13.92		54	16.61	
Total		359			325		109
	C. pelagicus	9	2.57				
	C. leptoporus	248	71.06				
	H. carteri	82	23.49				
	S. pulchra	8	2.29				
	U. sibogae	2	0.57				
Total		349					
MD88784	E. huxleyi	100	28.49				
Lat. 54°11.48S	G. muellerae	76	21.65				
2800m	G. oceanica	4	1.12				
HOLOCENE	G. caribbeanica	15	4.27				
	small Gephyrocapsa spp	71	20.22				
	Subordinate	85	24.21				
Total		351		31			
	C. pelagicus	6	1.65				
	C. leptoporus	249	68.78				
	C. macintyrei	9	2.48				
	H. carteri	72	19.88				
	O. fragilis	5	1.38				
	R. clavigera	8	2.2				
	R. gelida - large closed	4	1.1				
	U. tenuis	2	0.55				
	U. sibogae	9	2.48				
Total		362		72			
POLAR FRONT							
KR 8811							
Lat. 54°55.07S							
2880m							
Very few coccoliths. Mostly diatoms.							
MD 88786							
Lat. 54°55.86S							
2910m							
Barren of coccoliths. All diatoms.							
MD 88787							
Lat. 56°22.72S							
3020m							
Coccoliths are rare, a few E. huxleyi. Mostly diatoms.							
MD 88788							
Lat. 57°56.57S							
3742m							
Barren of coccoliths. All diatoms.							
KR 8813							
Lat 57°56.86S							
3740m							
Coccoliths are rare, a few C. leptoporus and G. muellerae. Mostly diatoms.							
These samples are listed with reference to their proximity to the fronts based on the positions given by Belkin and Gordon, 1996.							
The latitude position is not in consecutive order as it is based on the longitude position and the proximity of the fronts.							

Appendix A3

Cores GC04, GC120, GC32, GC32, GC34 and GC35

CORE	DEPTH IN CORE	COUNT TO ~300	SPECIMENS	Percentage
	cm	species identified	No. identified	
GC04	0-1	Emiliania huxleyi	97	21.79
Lat. 44°05.99S		Gephyrocapsa mullerae	120	23.59
2981m		Gephyrocapsa oceanica	9	2.02
		Coccolithus pelagicus	35	7.86
		Calcidiscus leptoporus	158	35.5
		Helicosphaera carteri	32	7.19
		Umbellosphaera sibogae	3	0.67
		Reticulofenestra pseudoumbilica - large, open	5	1.12
		Reticulofenestra sp. - small, closed	3	0.67
			447	
	5-8	Radiocarbon date - 3,160yr BP +/- 72yr		
	50-53	E. huxleyi	42	14.58
		G. muellerae	150	52.08
		G. oceanica	22	7.63
		G. caribbeanica	13	4.51
		C. pelagicus	16	5.55
		C. leptoporus	35	12.15
		H. carteri	10	3.47
			288	
	171-174	E. huxleyi	28	7.1
		G. muellerae	196	49.74
		G. oceanica	39	9.89
		C. pelagicus	30	7.61
		C. leptoporus	90	22.84
		H. carteri	10	2.53
		U. sibogae	1	0.25
			394	
	249-252	E. huxleyi	20	3.9
		G. muellerae	366	71.48
		G. oceanica	8	1.56
		C. pelagicus	55	10.74
		C. leptoporus	52	10.15
		H. carteri	7	1.36
		U. sibogae	2	0.39
		Calcidiscus macintyrei	2	0.39
			512	
GC20	coretop	Emiliania huxleyi	39	7.48
48°39.03S		Gephyrocapsa muellerae	372	71.4
3300m		Gephyrocapsa oceanica	13	2.49
		Coccolithus pelagicus	28	5.37
		Calcidiscus leptoporus	61	11.7
		Helicosphaera carteri	6	1.15
		Umbellosphaera angustiforamen	1	0.19
		Reticulofenestra sp. - small, closed	1	0.19
			521	
	48-50	E. huxleyi	64	13.25
		G. muellerae	296	61.28
		G. oceanica	17	3.51
		C. pelagicus	45	9.31
		C. leptoporus	53	10.97
		H. carteri	4	0.82
		Umbellosphaera sibogae	4	0.82
			483	
	128-130	E. huxleyi	57	12.39
		G. muellerae	313	68.04
		G. oceanica	21	4.56
		C. pelagicus	9	1.95
		C. leptoporus	54	11.73
		H. carteri	5	1.08
		U. sibogae	1	0.21
			460	
GC31	0-1	Emiliania huxleyi	61	18.15
44°32.79S		Gephyrocapsa muellerae	89	26.48
3440m		Gephyrocapsa oceanica	26	7.73
		Coccolithus pelagicus	45	13.39
		Calcidiscus leptoporus	86	25.59
		Helicosphaera carteri	17	5.05
		Umbellosphaera sibogae	1	0.29
		Rhabdosphaera clavigera	3	0.89
		Syracosphaera anthos	6	1.78
		Reticulofenestra sp. - small, closed	2	0.59
			336	
	75-78	E. huxleyi	13	3.95
		G. muellerae	121	36.77
		G. caribbeanica	2	0.6
		G. oceanica	1	0.3
		C. pelagicus	36	10.94
		C. leptoporus	31	9.42
		H. carteri	3	0.91
		U. sibogae	1	0.3
		C. macintyrei	19	5.77
		Discoaster sp.	1	0.3
		U. angustiforamen	3	0.9
		Pseudoemiliania lacunosa	2	0.6
		Reticulofenestra pseudoumbilica - large, open	32	9.72
		Reticulofenestra sp. - small, closed	15	4.55
		Reticulofenestra sp. - smal, closed	49	14.89
			329	

Appendix A3

Cores GC04, GC120, GC32, GC32, GC34 and GC35

CORE	DEPTH IN CORE cm	COUNT TO ~300 species identified	SPECIMENS No. identified	Percentage
GC31	205-208	E. huxleyi	13	2.63
44°32.79S		G. muellerae	376	76.26
3440m		G. oceanica	34	6.89
		C. pelagicus	36	7.3
		C. leptoporus	21	4.25
		H. carteri	3	0.6
		U. angustiforamen	1	0.2
		Reticulofenestra sp. - small, closed	2	0.4
		Reticulofenestra pseudoumbilica - large, open	7	1.41
			493	
GC32	coretop	Emiliania huxleyi	66	15.71
43°57.93S		Gephyrocapsa muellerae	111	26.42
2650m		Gephyrocapsa oceanica	29	6.9
		Coccolithus pelagicus	58	13.8
		Calcidiscus leptoporus	126	30
		Helicosphaera carteri	23	5.47
		Umbellosphaera angustiforamen	4	0.95
		Rhabdosphaera clavigera	1	0.23
		Reticulofenestra gelida - large, closed	2	0.47
			420	
	60-63	E. huxleyi	18	3.06
		G. muellerae	443	75.34
		G. caribbeanica	9	3.23
		C. pelagicus	62	10.54
		C. leptoporus	35	5.95
		H. carteri	4	0.68
		Reticulofenestra sp. - small, closed	7	1.19
			588	
	173-175	E. huxleyi	0	
		G. muellerae	440	79.85
		G. oceanica	5	0.9
		G. caribbeanica	42	7.62
		C. pelagicus	17	3.08
		C. leptoporus	34	6.17
		H. carteri	8	1.45
		U. sibogae	1	0.18
		C. macintyrei	1	0.18
		Reticulofenestra sp. - small, closed	3	0.54
			551	
GC34	0-1	Emiliania huxleyi	34	8.71
45°06.00S		Gephyrocapsa muellerae	99	25.38
4202m		Gephyrocapsa oceanica	23	5.89
		Coccolithus pelagicus	87	22.3
		Calcidiscus leptoporus	130	33.33
		Helicosphaera carteri	8	2.05
		Syracosphaera anthos	3	0.76
		Umbellosphaera sibogae	1	0.25
		Reticulofenstra sp. - small, closed	5	1.28
			390	
	50-52	E. huxleyi	4	0.84
		G. muellerae	186	39.4
		G. oceanica	3	0.63
		G. caribbeanica	5	3.17
		C. pelagicus	136	28.81
		C. leptoporus	112	23.72
		H. carteri	4	0.84
		Reticulofenestra sp. - small, closed	12	2.54
			472	
	120-122	E. huxleyi	0	0
		G. muellerae	230	50.99
		G. oceanica	20	4.43
		C. pelagicus	111	24.61
		C. leptoporus	49	10.86
		R. clavigera	1	0.22
		H. carteri	6	1.33
		Reticulofenestra sp. - small, closed	34	7.53
			451	
	420-422	E. huxleyi	13	2.36
		G. muellerae	389	70.85
		G. oceanica	15	2.73
		G. caribbeanica	25	4.55
		C. pelagicus	34	6.19
		C. leptoporus	37	6.73
		H. carteri	4	0.72
		Reticulofenestra sp. - small, closed	32	5.82
			549	
	505-507	E. huxleyi	3	0.64
		G. muellerae	231	49.57
		G. oceanica	1114	2.36
		G. caribbeanica	25	3
		C. pelagicus	117	25.1
		C. leptoporus	90	19.31
			466	
GC35	0-1	Emiliania huxleyi	7	2.12
45°44.00S		Gephyrocapsa muellerae	154	46.66
2720m		Gephyrocapsa caribbeanica	112	33.93
		Gephyrocapsa oceanica	8	2.42
		Coccolithus pelagicus	37	11.21
		Calcidiscus leptoporus	17	5.15
		Helicosphaera carteri	2	2.12
			330	

Appendix A3

Cores GC04, GC120, GC32, GC32, GC34 and GC35

CORE	DEPTH IN CORE	COUNT TO ~300	SPECIMENS	Percentage
	cm	species identified	No. identified	
GC35	55-57	E. huxleyi	7	1.82
45°44.00S		G. muellerae	201	52.48
2720m		G. oceanica	33	8.61
		G. caribbeanica	104	27.15
		C. pelagicus	12	3.13
		C. leptoporus	23	6
		H. carteri	3	0.78
			383	
	125-127	E. huxleyi	0	0
		G. caribbeanica	131	42.25
		G. muellerae	66	21.29
		G. oceanica	13	4.19
		small Gephyrocapsa spp	10	3.22
		C. pelagicus	44	36.12
		C. leptoporus	38	12.25
		Reticulofenestra pseudoumbilica - large, open	1	0.32
		H. carteri	7	2.25
			310	

Appendix A4 - Surface sediment samples 73 ka yr BP or younger.
Subordinate species only listed in order related to latitude and position of oceanic fronts.

Core Number	Species Identified	Light Microscope Count one	No. of screens 1mmx1mm	Percentage of species	Electron Microscope Count One	No. of screens 36x46µm	Percentage of species
147/GC007	Coccolithus pelagicus	8		2.25	73		20.73
Lat. 45°09'S	Calcidiscus leptoporus	211		59.43	235		66.76
Long. 146°17'E	Helicosphaera carteri	76		21.4	42		11.93
3307m	Oolithus fragilis	4		1.12			
Holocene coretop	Reworked spp	1		0.28	3		0.85
	Syracosphaera pulchra	43		12.11	6		1.7
	Umbilicosphaera sibogae	12		3.38	5		1.42
Total		355	127		352	220	
SUBTROPICAL FRONT (~46°S-47°S south of Australia; ~45°S east of New Zealand)							
MD972118	C. pelagicus	12		3.23	20		5.3
Lat. 45°07'S	C. leptoporus	307		82.74	318		84.35
Long.179°10'W	H. carteri	29		7.81	20		5.3
2690m	Rhabdosphaera clavigera	0		0	4		1.06
	Reticulofenestra gelida - large closed	1		0.26	0		0
	Reticulofenestra sp. medium -open	1		0.26	0		0
	Reticulofenestra sp. medium - closed	1		0.26	0		0
	Reticulofenestra producta - small closed	1		0.26	0		0
	S. pulchra	3		0.8	5		1.32
	U. sibogae	5		1.34	6		1.59
	Umbellosphaera tenuis	12		3.23	4		1.06
Total		372	16		377		
MD972108	C. pelagicus	8		2.25	0		0
Lat. 48°29'S	C. leptoporus	275		77.68	315		88.23
Long. 149°06'E	H. carteri	33		9.32	37		10.36
2140m	R. clavigera	1		0.28	1		0.28
	S. pulchra	11		3.1	3		0.84
	U. sibogae	7		1.97	2		0.56
	U. tenuis	19		5.36	0		0
Total		354	17		357	139	
KR 8808	C. pelagicus	89		24.38			
Lat. 49°15'S	C. leptoporus	159		43.56			
Long. 148°48'E	Calcidiscus macintyrei	6		1.64			
3885m	H. carteri	88		24.10			
	O. fragilis	1		0.27			
	Reticulofenestra producta - small closed	2		0.54			
	Reticulofenestra - medium open	1		0.27			
	Reticulofenestra gelida - large closed	3		0.82			
	S. pulchra	3		0.82			
	U. tenuis	1		0.27			
	U. sibogae	13		3.56			
Total		365	78				
MD972110	C. pelagicus	8		2.14	0		0
Lat. 48°25'S	C. leptoporus	310		83.1	308		87.74
Long. 176°34'E	H. carteri	23		6.16	26		7.4
1345m	Reticulofenestra gelida - large closed	2		0.53	0		0
	Reticulofenestra sp. - medium closed	3		0.8	0		0
	S. pulchra	11		2.94	7		1.99
	U. sibogae	6		1.6	8		2.27
	U. tenuis	10		2.68	2		0.56
Total		373	13		351	137	
SUBANTARCTIC FRONT (~52°S-53°S south of Australia; ~50°S east of New Zealand)							
MD88783	C.pelagicus	7		1.84			
Lat. 52°23'S	C.leptoporus	277		73.08			
Long. 144°49'E	C. macintyrei	15		3.95			
3170m	H. carteri	43		11.34			
	R. gelida - large closed	3		0.79			
	Reticulofenestra sp. - medium closed	1		0.26			
	Reticulofenestra producta - small closed	7		1.84			
	S. pulchra	13		3.43			
	U. tenuis	4		1.05			
	U. sibogae	9		2.37			
Total		379	51				
POLAR FRONT (~54°S south of Australia)							
KR 8810	C. pelagicus	9		2.57			
Lat. 54°11'S	C. leptoporus	248		71.06			
Long. 144°47'E	H. carteri	82		23.49			
2785m	S. pulchra	8		2.29			
	U. sibogae	2		0.57			
Total		349					
MD88784	C. pelagicus	6		1.65			
Lat. 54°11'S	C. leptoporus	249		68.78			
Long. 144°47'E	C. floridanus	9		2.48			
2800m	H. carteri	72		19.88			
	Oolithus fragilis	5		1.38			
	R. clavigera	8		2.2			
	Reticulofenestra gelida - large closed	4		1.1			
	U. tenuis	2		0.55			
	U. sibogae	9		2.48			
Total		362	72				
POLAR FRONT (~54°S south of Australia)							

Appendix B1

Calcareous nannoplankton counts for austral summer 1994.

Filter diameter (mm)	40							
Dims. of screens (microns)	36	46						
Area of filter (mm2)	1256.63704							
Area of SEM screens (mm2)	0.001656							
Screens per filter	758838.792							
No. of screens counted:	445	567	400	500	400	400	440	400
Total number of coccospheres counted								
Sample:	CTD-16/14m	CTD-16/28m	CTD-16/53m	CTD-16/103m	CTD-16/152m	CTD-21/14m	CTD-21/29m	CTD-21/53m
Acanthoica quattrospina						1		
Calcidiscus leptoporus	60	30	24	2	13	9	15	12
Calciopappus rigidus				1				
Coronosphaera mediterranea			2					
Cyrtosphaera cucullata		1					1	1
Emiliania huxleyi - cold+polar	143	165	63	18	32	182	271	136
Helicosphaera carteri								
Ophiaster hydroideus		1				1		
Papposphaera obpyramidalis								
Papposphaera sagittifera								
Syracosphaera molischii					1			
Syracosphaera nodosa						4		
Syracosphaera sp.	2	1		2	1		1	2
Wigwamma antarctica								
Wigwamma triradiata								
Volume of filtrate	2	1	1	1	1.5	1	1	1
Number of coccospheres per litre of water								
Sample:	CTD-16/14m	CTD-16/28m	CTD-16/53m	CTD-16/103m	CTD-16/152m	CTD-21/14m	CTD-21/29m	CTD-21/53m
Acanthoica quattrospina	0	0	0	0	0	1897	0	0
Calcidiscus leptoporus	51158	40150	45530	3035	16442	17074	25870	22765
Calciopappus rigidus	0	0	0	1518	0	0	0	0
Coronosphaera mediterranea	0	0	3794	0	0	0	0	0
Cyrtosphaera cucullata	0	1338	0	0	0	0	1725	1897
Emiliania huxleyi - cold+polar	121926	220826	119517	27318	40471	345272	467376	258005
Helicosphaera carteri	0	0	0	0	0	0	0	0
Ophiaster hydroideus	0	1338	0	0	0	1897	0	0
Papposphaera obpyramidalis	0	0	0	0	0	0	0	0
Papposphaera sagittifera	0	0	0	0	0	0	0	0
Syracosphaera molischii	0	0	0	0	1265	0	0	0
Syracosphaera nodosa	0	0	0	0	0	7588	0	0
Syracosphaera sp.	1705	1338	0	3035	1265	0	1725	3794
Wigwamma antarctica	0	0	0	0	0	0	0	0
Wigwamma triradiata	0	0	0	0	0	0	0	0
Total coccospheres/ litre:	174789	264991	168842	34907	59442	373728	496694	286462
Percentage of species of Total								
Sample:	CTD-16/14m	CTD-16/28m	CTD-16/53m	CTD-16/103m	CTD-16/152m	CTD-21/14m	CTD-21/29m	CTD-21/53m
Acanthoica quattrospina	0.00%	0.00%	0.00%	0.00%	0.00%	0.51%	0.00%	0.00%
Calcidiscus leptoporus	29.27%	15.15%	26.97%	8.70%	27.66%	4.57%	5.21%	7.95%
Calciopappus rigidus	0.00%	0.00%	0.00%	4.35%	0.00%	0.00%	0.00%	0.00%
Coronosphaera mediterranea	0.00%	0.00%	2.25%	0.00%	0.00%	0.00%	0.00%	0.00%
Cyrtosphaera cucullata	0.00%	0.51%	0.00%	0.00%	0.00%	0.00%	0.35%	0.66%
Emiliania huxleyi - cold+polar	69.76%	83.33%	70.79%	78.26%	68.09%	92.39%	94.10%	90.07%
Helicosphaera carteri	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Ophiaster hydroideus	0.00%	0.51%	0.00%	0.00%	0.00%	0.51%	0.00%	0.00%
Papposphaera obpyramidalis	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Papposphaera sagittifera	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Syracosphaera molischii	0.00%	0.00%	0.00%	0.00%	2.13%	0.00%	0.00%	0.00%
Syracosphaera nodosa	0.00%	0.00%	0.00%	0.00%	0.00%	2.03%	0.00%	0.00%
Syracosphaera sp.	0.98%	0.51%	0.00%	8.70%	2.13%	0.00%	0.35%	1.32%
Wigwamma antarctica	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Wigwamma triradiata	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Percentage of subordinate species per litre without reference to E. huxleyi								
Sample:	CTD-16/14m	CTD-16/28m	CTD-16/53m	CTD-16/103m	CTD-16/152m	CTD-21/14m	CTD-21/29m	CTD-21/53m
Acanthoica quattrospina	0.00%	0.00%	0.00%	0.00%	0.00%	6.67%	0.00%	0.00%
Calcidiscus leptoporus	96.77%	90.91%	92.31%	40.00%	86.67%	60.00%	88.24%	80.00%
Calciopappus rigidus	0.00%	0.00%	0.00%	20.00%	0.00%	0.00%	0.00%	0.00%
Coronosphaera mediterranea	0.00%	0.00%	7.69%	0.00%	0.00%	0.00%	0.00%	0.00%
Cyrtosphaera cucullata	0.00%	3.03%	0.00%	0.00%	0.00%	0.00%	5.88%	6.67%
Helicosphaera carteri	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Ophiaster hydroideus	0.00%	3.03%	0.00%	0.00%	0.00%	6.67%	0.00%	0.00%
Papposphaera obpyramidalis	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Papposphaera sagittifera	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Syracosphaera molischii	0.00%	0.00%	0.00%	0.00%	6.67%	0.00%	0.00%	0.00%
Syracosphaera nodosa	0.00%	0.00%	0.00%	0.00%	0.00%	26.67%	0.00%	0.00%
Syracosphaera sp.	3.23%	3.03%	0.00%	40.00%	6.67%	0.00%	5.88%	13.33%
Wigwamma antarctica	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Wigwamma triradiata	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

Appendix B1

Calcareous nannoplankton counts for austral summer 1994.

No. of screens counted:	400	400	400	400	480	400	400	400
Total number of coccospheres counted								
Sample:	CTD-21/103m	CTD-21/156m	CTD-30/13m	CTD-30/53m	CTD-30/77m	CTD-30/103m	CTD-30/154m	CTD-37/14m
Acanthoica quattrospina								
Calcidiscus leptoporus	15	6		1				
Calciopappus rigidus	1							
Coronosphaera mediterranea								
Cyrtosphaera cucullata								
Emiliania huxleyi - cold+polar	20	14	87	103	113	67	46	129
Helicosphaera carteri	1							
Ophiaster hydroideus								
Papposphaera obpyramidalis								
Papposphaera sagittifera								
Syracosphaera molischii								
Syracosphaera nodosa								
Syracosphaera sp.								
Wigwamma antarctica								
Wigwamma triradiata								
Volume of filtrate	1.5	1.5	1	1	1	1.55	1.5	1.5
Number of coccospheres per litre of water								
Sample:	CTD-21/103m	CTD-21/156m	CTD-30/13m	CTD-30/53m	CTD-30/77m	CTD-30/103m	CTD-30/154m	CTD-37/14m
Acanthoica quattrospina	0	0	0	0	0	0	0	0
Calcidiscus leptoporus	18971	7588	0	1897	0	0	0	0
Calciopappus rigidus	1265	0	0	0	0	0	0	0
Coronosphaera mediterranea	0	0	0	0	0	0	0	0
Cyrtosphaera cucullata	0	0	0	0	0	0	0	0
Emiliania huxleyi - cold+polar	25295	17706	165047	195401	178643	82004	58178	163150
Helicosphaera carteri	1265	0	0	0	0	0	0	0
Ophiaster hydroideus	0	0	0	0	0	0	0	0
Papposphaera obpyramidalis	0	0	0	0	0	0	0	0
Papposphaera sagittifera	0	0	0	0	0	0	0	0
Syracosphaera molischii	0	0	0	0	0	0	0	0
Syracosphaera nodosa	0	0	0	0	0	0	0	0
Syracosphaera sp.	0	0	0	0	0	0	0	0
Wigwamma antarctica	0	0	0	0	0	0	0	0
Wigwamma triradiata	0	0	0	0	0	0	0	0
Total coccospheres/ litre:	46795	25295	165047	197298	178643	82004	58178	163150
Percentage of of species per litre of water								
Sample:	CTD-21/103m	CTD-21/156m	CTD-30/13m	CTD-30/53m	CTD-30/77m	CTD-30/103m	CTD-30/154m	CTD-37/14m
Acanthoica quattrospina	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Calcidiscus leptoporus	40.54%	30.00%	0.00%	0.96%	0.00%	0.00%	0.00%	0.00%
Calciopappus rigidus	2.70%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Coronosphaera mediterranea	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Cyrtosphaera cucullata	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Emiliania huxleyi - cold+polar	54.05%	70.00%	100.00%	99.04%	100.00%	100.00%	100.00%	100.00%
Helicosphaera carteri	2.70%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Ophiaster hydroideus	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Papposphaera obpyramidalis	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Papposphaera sagittifera	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Syracosphaera molischii	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Syracosphaera nodosa	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Syracosphaera sp.	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Wigwamma antarctica	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Wigwamma triradiata	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Percentage of subordinate species per litre without reference to E. huxleyi								
Sample:	CTD-21/103m	CTD-21/156m	CTD-30/13m	CTD-30/53m	CTD-30/77m	CTD-30/103m	CTD-30/154m	CTD-37/14m
Acanthoica quattrospina	0.00%	0.00%		0.00%				
Calcidiscus leptoporus	88.24%	100.00%		100.00%				
Calciopappus rigidus	5.88%	0.00%		0.00%				
Coronosphaera mediterranea	0.00%	0.00%		0.00%				
Cyrtosphaera cucullata	0.00%	0.00%		0.00%				
Helicosphaera carteri	5.88%	0.00%		0.00%				
Ophiaster hydroideus	0.00%	0.00%		0.00%				
Papposphaera obpyramidalis	0.00%	0.00%		0.00%				
Papposphaera sagittifera	0.00%	0.00%		0.00%				
Syracosphaera molischii	0.00%	0.00%		0.00%				
Syracosphaera nodosa	0.00%	0.00%		0.00%				
Syracosphaera sp.	0.00%	0.00%		0.00%				
Wigwamma antarctica	0.00%	0.00%		0.00%				
Wigwamma triradiata	0.00%	0.00%		0.00%				

Appendix B1

Calcareous nannoplankton counts for austral summer 1994.

No. of screens counted:	400	400	400	400	400	400	400	400
Total number of coccospheres counted								
Sample:	CTD-37/53m	CTD-37/103m	CTD-37/152m	CTD-39/13m	CTD-39/62m	CTD-39/102m	CTD-43/13m	CTD-43/42m
Acanthoica quattrospina								
Calcidiscus leptoporus								
Calciopappus rigidus								
Coronosphaera mediterranea								
Cyrtosphaera cucullata								
Emiliania huxleyi - cold+polar	73	52	50	103	88	63	73	15
Helicosphaera carteri								
Ophiaster hydroideus								
Papposphaera obpyramidalis								
Papposphaera sagittifera								
Syracosphaera molischii								
Syracosphaera nodosa								
Syracosphaera sp.								
Wigwamma antarctica								
Wigwamma triradiata								
Volume of filtrate	1.5	2	2	1	1	1.67	1	1
Number of coccospheres per litre of water								
Sample:	CTD-37/53m	CTD-37/103m	CTD-37/152m	CTD-39/13m	CTD-39/62m	CTD-39/102m	CTD-43/13m	CTD-43/42m
Acanthoica quattrospina	0	0	0	0	0	0	0	0
Calcidiscus leptoporus	0	0	0	0	0	0	0	0
Calciopappus rigidus	0	0	0	0	0	0	0	0
Coronosphaera mediterranea	0	0	0	0	0	0	0	0
Cyrtosphaera cucullata	0	0	0	0	0	0	0	0
Emiliania huxleyi - cold+polar	92325	49325	47427	195401	166945	71567	138488	28456
Helicosphaera carteri	0	0	0	0	0	0	0	0
Ophiaster hydroideus	0	0	0	0	0	0	0	0
Papposphaera obpyramidalis	0	0	0	0	0	0	0	0
Papposphaera sagittifera	0	0	0	0	0	0	0	0
Syracosphaera molischii	0	0	0	0	0	0	0	0
Syracosphaera nodosa	0	0	0	0	0	0	0	0
Syracosphaera sp.	0	0	0	0	0	0	0	0
Wigwamma antarctica	0	0	0	0	0	0	0	0
Wigwamma triradiata	0	0	0	0	0	0	0	0
Total coccospheres/ litre:	92325	49325	47427	195401	166945	71567	138488	28456
Percentage of of species per litre of water								
Sample:	CTD-37/53m	CTD-37/103m	CTD-37/152m	CTD-39/13m	CTD-39/62m	CTD-39/102m	CTD-43/13m	CTD-43/42m
Acanthoica quattrospina	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Calcidiscus leptoporus	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Calciopappus rigidus	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Coronosphaera mediterranea	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Cyrtosphaera cucullata	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Emiliania huxleyi - cold+polar	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%
Helicosphaera carteri	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Ophiaster hydroideus	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Papposphaera obpyramidalis	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Papposphaera sagittifera	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Syracosphaera molischii	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Syracosphaera nodosa	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Syracosphaera sp.	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Wigwamma antarctica	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Wigwamma triradiata	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Percentage of subordinate species per litre without reference to E. huxleyi								
Sample:	CTD-37/53m	CTD-37/103m	CTD-37/152m	CTD-39/13m	CTD-39/62m	CTD-39/102m	CTD-43/13m	CTD-43/42m
Acanthoica quattrospina								
Calcidiscus leptoporus								
Calciopappus rigidus								
Coronosphaera mediterranea								
Cyrtosphaera cucullata								
Helicosphaera carteri								
Ophiaster hydroideus								
Papposphaera obpyramidalis								
Papposphaera sagittifera								
Syracosphaera molischii								
Syracosphaera nodosa								
Syracosphaera sp.								
Wigwamma antarctica								
Wigwamma triradiata								

Appendix B1

Calcareous nannoplankton counts for austral summer 1994.

No. of screens counted:	400	400	400	400	400	400	400	400
Total number of coccospheres counted								
Sample:	CTD-43/127m	CTD-47/14m	CTD-47/45m	CTD-47/130m	CTD-47/184m	CTD-51/13m	CTD-51/55m	CTD-51/103m
Acanthoica quattrospina								
Calcidiscus leptoporus								
Calciopappus rigidus								
Coronosphaera mediterranea								
Cyrtosphaera cucullata								
Emiliania huxleyi - cold+polar	69	105	129	28	273	7	5	4
Helicosphaera carteri								
Ophiaster hydroideus								
Pappasphaera obpyramidalis								
Pappasphaera sagittifera				2				
Syracosphaera molischii								
Syracosphaera nodosa								
Syracosphaera sp.								
Wigwamma antarctica								
Wigwamma triradiata								
Volume of filtrate	1.6	1	1	2	2	1	1	1
Number of coccospheres per litre of water								
Sample:	CTD-43/127m	CTD-47/14m	CTD-47/45m	CTD-47/130m	CTD-47/184m	CTD-51/13m	CTD-51/55m	CTD-51/103m
Acanthoica quattrospina	0	0	0	0	0	0	0	0
Calcidiscus leptoporus	0	0	0	0	0	0	0	0
Calciopappus rigidus	0	0	0	0	0	0	0	0
Coronosphaera mediterranea	0	0	0	0	0	0	0	0
Cyrtosphaera cucullata	0	0	0	0	0	0	0	0
Emiliania huxleyi - cold+polar	81812	199195	244726	26559	258954	13280	9485	7588
Helicosphaera carteri	0	0	0	0	0	0	0	0
Ophiaster hydroideus	0	0	0	0	0	0	0	0
Pappasphaera obpyramidalis	0	0	0	0	0	0	0	0
Pappasphaera sagittifera	0	0	0	1897	0	0	0	0
Syracosphaera molischii	0	0	0	0	0	0	0	0
Syracosphaera nodosa	0	0	0	0	0	0	0	0
Syracosphaera sp.	0	0	0	0	0	0	0	0
Wigwamma antarctica	0	0	0	0	0	0	0	0
Wigwamma triradiata	0	0	0	0	0	0	0	0
Total coccospheres/ litre:	81812	199195	244726	28456	258954	13280	9485	7588
Percentage of of species per litre of water								
Sample:	CTD-43/127m	CTD-47/14m	CTD-47/45m	CTD-47/130m	CTD-47/184m	CTD-51/13m	CTD-51/55m	CTD-51/103m
Acanthoica quattrospina	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Calcidiscus leptoporus	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Calciopappus rigidus	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Coronosphaera mediterranea	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Cyrtosphaera cucullata	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Emiliania huxleyi - cold+polar	100.00%	100.00%	100.00%	93.33%	100.00%	100.00%	100.00%	100.00%
Helicosphaera carteri	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Ophiaster hydroideus	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Pappasphaera obpyramidalis	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Pappasphaera sagittifera	0.00%	0.00%	0.00%	6.67%	0.00%	0.00%	0.00%	0.00%
Syracosphaera molischii	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Syracosphaera nodosa	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Syracosphaera sp.	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Wigwamma antarctica	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Wigwamma triradiata	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Percentage of subordinate species per litre without reference to E. huxleyi								
Sample:	CTD-43/127m	CTD-47/14m	CTD-47/45m	CTD-47/130m	CTD-47/184m	CTD-51/13m	CTD-51/55m	CTD-51/103m
Acanthoica quattrospina				0.00%				
Calcidiscus leptoporus				0.00%				
Calciopappus rigidus				0.00%				
Coronosphaera mediterranea				0.00%				
Cyrtosphaera cucullata				0.00%				
Helicosphaera carteri				0.00%				
Ophiaster hydroideus				0.00%				
Pappasphaera obpyramidalis				0.00%				
Pappasphaera sagittifera				100.00%				
Syracosphaera molischii				0.00%				
Syracosphaera nodosa				0.00%				
Syracosphaera sp.				0.00%				
Wigwamma antarctica				0.00%				
Wigwamma triradiata				0.00%				

Appendix B1

Calcareous nannoplankton counts for austral summer 1994.

No. of screens counted:	400	900	400	400	998	400	300	400	400
Total number of coccospheres counted									
Sample:	CTD-51/145m	CTD-54/13m	CTD-54/54m	CTD-54/103m	CTD-54/135m	CTD-59/14m	CTD-59/56m	CTD-59/103m	CTD-59/153m
Acanthoica quattrospina									
Calcidiscus leptoporus									
Calciopappus rigidus									
Coronosphaera mediterranea									
Cyrtosphaera cucullata									
Emiliania huxleyi - cold+polar	0	20	27	4	3				
Helicosphaera carteri									
Ophiaster hydroideus									
Papposphaera obpyramidalis					1				
Papposphaera sagittifera				1					
Syracosphaera molischii									
Syracosphaera nodosa									
Syracosphaera sp.									
Wigwamma antarctica				1					
Wigwamma triradiata				1					
Volume of filtrate		1.1	1.8	1.6	1.45	2	2	1.62	1
Number of coccospheres per litre of water									
Sample:	CTD-51/145m	CTD-54/13m	CTD-54/54m	CTD-54/103m	CTD-54/135m	CTD-59/14m	CTD-59/56m	CTD-59/103m	CTD-59/153m
Acanthoica quattrospina		0	0	0	0				
Calcidiscus leptoporus		0	0	0	0				
Calciopappus rigidus		0	0	0	0				
Coronosphaera mediterranea		0	0	0	0				
Cyrtosphaera cucullata		0	0	0	0				
Emiliania huxleyi - cold+polar		15330	28456	4743	1573				
Helicosphaera carteri		0	0	0	0				
Ophiaster hydroideus		0	0	0	0				
Papposphaera obpyramidalis		0	0	0	524				
Papposphaera sagittifera		0	0	1186	0				
Syracosphaera molischii		0	0	0	0				
Syracosphaera nodosa		0	0	0	0				
Syracosphaera sp.		0	0	0	0				
Wigwamma antarctica		0	0	1186	0				
Wigwamma triradiata		0	0	1186	0				
Total coccospheres/ litre:	0	15330	28456	8300	2098	0	0	0	0
Percentage of of species per litre of water									
Sample:	CTD-51/145m	CTD-54/13m	CTD-54/54m	CTD-54/103m	CTD-54/135m	CTD-59/14m	CTD-59/56m	CTD-59/103m	CTD-59/153m
Acanthoica quattrospina		0.00%	0.00%	0.00%	0.00%				
Calcidiscus leptoporus		0.00%	0.00%	0.00%	0.00%				
Calciopappus rigidus		0.00%	0.00%	0.00%	0.00%				
Coronosphaera mediterranea		0.00%	0.00%	0.00%	0.00%				
Cyrtosphaera cucullata		0.00%	0.00%	0.00%	0.00%				
Emiliania huxleyi - cold+polar		100.00%	100.00%	57.14%	75.00%				
Helicosphaera carteri		0.00%	0.00%	0.00%	0.00%				
Ophiaster hydroideus		0.00%	0.00%	0.00%	0.00%				
Papposphaera obpyramidalis		0.00%	0.00%	0.00%	25.00%				
Papposphaera sagittifera		0.00%	0.00%	14.29%	0.00%				
Syracosphaera molischii		0.00%	0.00%	0.00%	0.00%				
Syracosphaera nodosa		0.00%	0.00%	0.00%	0.00%				
Syracosphaera sp.		0.00%	0.00%	0.00%	0.00%				
Wigwamma antarctica		0.00%	0.00%	14.29%	0.00%				
Wigwamma triradiata		0.00%	0.00%	14.29%	0.00%				
Percentage of subordinate species per litre without reference to E. huxleyi									
Sample:	CTD-51/145m	CTD-54/13m	CTD-54/54m	CTD-54/103m	CTD-54/135m	CTD-59/14m	CTD-59/56m	CTD-59/103m	CTD-59/153m
Acanthoica quattrospina				0.00%	0.00%				
Calcidiscus leptoporus				0.00%	0.00%				
Calciopappus rigidus				0.00%	0.00%				
Coronosphaera mediterranea				0.00%	0.00%				
Cyrtosphaera cucullata				0.00%	0.00%				
Helicosphaera carteri				0.00%	0.00%				
Ophiaster hydroideus				0.00%	0.00%				
Papposphaera obpyramidalis				0.00%	100.00%				
Papposphaera sagittifera				33.33%	0.00%				
Syracosphaera molischii				0.00%	0.00%				
Syracosphaera nodosa				0.00%	0.00%				
Syracosphaera sp.				0.00%	0.00%				
Wigwamma antarctica				33.33%	0.00%				
Wigwamma triradiata				33.33%	0.00%				

Appendix B2

Calcareous nannoplankton counts for austral summer 1994

Filter diameter (mm)	40											
No. of SEM screens	400											
Dims. of screens (microns)	36	46										
Area of filter (mm2)	1256.63704											
Area of SEM screens (mm2)	0.001656											
Screens per filter	758838.792											
Sample	HC001 -12m	HC001 -56m	HC001 -110m	HC001 -164m	HC001 - 218m	HC002 -14m	HC002 -28m	HC002 -55m	HC002 -110m	HC002 -163m	HC004 -17m	HC004 -34m
Coccospheres / 400 screens:												
Acanthoica quattrospina	1	2	0	0	1	0	0	0	0	1	8	5
Alisphaera unicornis	0	0	0	0	0	0	0	0	0	0	0	0
Calcidiscus leptoporus	0	2	1	1	0	0	0	1	1	0	5	0
Calciopappus rigidus	0	1	0	0	0	0	0	0	0	0	0	0
Calciosolenia murrayi	0	0	0	0	0	2	3	0	0	0	7	4
Calicasphaera diconstricta	0	0	0	0	0	0	0	0	0	0	0	0
Calyptrolithophora papillifera	1	0	0	0	0	0	0	0	0	0	0	0
Corisphaera gracilis	0	0	0	0	0	0	0	0	0	0	0	0
Coronosphaera mediterranea	2	0	0	0	3	2	1	4	1	0	0	4
Cyrtosphaera cucullata	0	0	0	0	0	0	0	0	0	0	0	75
Discosphaera tubifera	0	0	0	0	0	0	0	0	0	0	0	0
Emiliania huxleyi - cold	36	452	41	21	42	29	20	44	14	21	78	61
Emiliania huxleyi - warm	44	364	7	8	53	55	37	143	58	132	93	0
Emiliania huxleyi - polar	0	0	0	0	0	0	0	0	0	0	0	0
Gephyrocapsa ericsonii	0	0	0	0	0	0	0	0	0	0	0	0
Gephyrocapsa muellerae	2	21	6	1	1	2	0	4	0	0	1	1
Helicosphaera carteri	0	0	0	0	0	0	0	0	3	0	0	0
Holococcolithophorid sp.	4	0	1	0	0	0	0	0	0	0	0	0
Michaelsarsia elegans	0	0	0	0	0	0	0	0	1	0	0	1
Ophiaster hydroideus	0	2	0	0	0	0	0	2	0	0	0	0
Pappomonas weddellensis	0	0	0	0	0	0	0	0	0	0	0	1
Papposphaera sagittifera	0	0	0	0	0	0	0	0	0	0	0	0
Papposphaera lepida	0	0	0	0	0	0	0	0	0	0	0	3
Polycrater galapagensis	0	0	0	0	0	0	0	0	0	0	0	0
Sphaerocalyptra quadridentata	0	0	0	0	0	0	0	0	0	0	0	0
Syracosphaera anthos	0	0	0	0	0	0	0	0	0	0	0	0
Syracosphaera corolla	5	0	0	0	1	0	3	2	0	0	1	0
Syracosphaera halldalii	0	0	0	0	0	0	0	0	0	0	0	0
Syracosphaera histrica	2	0	0	0	0	0	0	0	0	0	0	0
Syracosphaera molischii	14	4	1	3	2	6	5	3	3	2	4	6
Syracosphaera nana	0	0	0	0	0	0	0	0	0	0	0	0
Syracosphaera nodosa	4	3	0	0	3	4	7	4	0	1	13	6
Syracosphaera ossa	0	2	0	0	0	0	0	0	0	0	0	0
Syracosphaera pulchra	0	3	0	2	2	0	3	1	4	4	3	0
Syracosphaera rotula	0	2	0	0	0	0	0	0	0	0	0	0
Syracosphaera sp.	2	5	0	0	3	0	0	1	2	0	3	1
Umbellosphaera tenuis	41	15	0	0	38	28	0	2	0	0	3	3
Zygosphaera hellenica	0	0	0	0	0	0	0	0	0	0	0	0
Zygosphaera marsilii	0	0	0	0	0	0	0	0	0	0	0	0

Appendix B2

Calcareous nannoplankton counts for austral summer 1994

Filter diameter (mm)											
No. of SEM screens											
Dims. of screens (microns)											
Area of filter (mm2)											
Area of SEM screens (mm2)											
Screens per filter											
Sample	HC004 -62m	HC004 -120m	HC004 -180m	HC004 -240m	HC005 -19m	HC005 -35m	HC005 - 62m	HC005 -117m	HC005 -172m	HC005 -227m	HC007 -19m
Coccospheres/ 400 screens:											
Acanthoica quattrospina	1	0	0	0	3	5	5	0	0	0	0
Alisphaera unicornis	0	0	0	0	0	0	0	0	0	0	0
Calcidiscus leptoporus	8	1	0	0	0	1	0	3	2	0	5
Calciopappus rigidus	1	0	0	0	0	0	1	0	0	0	0
Calciosolenia murrayi	3	0	0	0	0	1	1	0	0	0	0
Calicasphaera diconstricta	0	0	0	0	0	0	0	0	0	0	0
Calyptrolithophora papillifera	0	0	0	0	0	0	0	0	0	0	0
Corisphaera gracilis	0	0	0	0	0	0	0	0	0	0	0
Coronosphaera mediterranea	0	0	0	0	0	0	0	0	0	0	0
Cyrtosphaera cucullata	0	0	0	0	3	3	0	0	0	0	0
Discosphaera tubifera	0	0	0	0	0	0	0	0	0	0	0
Emiliania huxleyi - cold	226	61	4	6	61	49	50	43	16	10	95
Emiliania huxleyi - warm	235	81	15	12	32	23	27	16	15	4	6
Emiliania huxleyi - polar	0	0	0	0	0	0	0	0	0	6	11
Gephyrocapsa ericsonii	0	0	0	0	0	0	0	0	0	0	0
Gephyrocapsa muellerae	3	0	0	0	0	0	0	0	0	0	0
Helicosphaera carteri	0	0	0	0	0	0	0	0	0	0	0
Holococcolithophorid sp.	0	0	0	0	5	2	2	0	0	0	0
Michaelsarsia elegans	2	0	0	0	0	4	0	0	0	0	0
Ophiaster hydroideus	0	0	0	0	0	0	8	0	0	0	0
Pappomonas weddellensis	0	1	0	0	0	0	0	0	0	0	0
Papposphaera sagittifera	0	0	0	0	2	0	0	0	0	0	0
Papposphaera lepida	0	0	0	0	0	0	0	0	0	0	0
Polycrater galapagensis	0	0	0	0	0	0	1	0	0	0	0
Sphaerocalyptra quadridentata	0	0	0	0	0	0	1	0	0	0	0
Syracosphaera anthos	1	0	0	0	0	0	0	0	0	0	0
Syracosphaera corolla	1	0	0	0	5	5	2	1	0	0	0
Syracosphaera halldalii	0	0	0	0	1	4	2	0	0	0	0
Syracosphaera histrica	0	0	0	0	0	0	0	1	0	0	0
Syracosphaera molischii	23	0	1	0	7	10	5	0	2	0	2
Syracosphaera nana	0	0	0	0	0	0	0	0	0	0	0
Syracosphaera nodosa	0	0	1	0	10	14	10	1	0	0	4
Syracosphaera ossa	0	0	0	0	0	0	1	0	0	0	0
Syracosphaera pulchra	0	1	1	1	3	3	1	4	0	0	1
Syracosphaera rotula	0	0	0	0	0	0	0	0	0	0	0
Syracosphaera sp.	2	0	0	0	0	0	4	0	1	0	0
Umbellosphaera tenuis	2	0	0	0	5	2	1	0	0	0	0
Zygosphaera hellenica	0	0	0	0	0	0	0	0	0	0	0
Zygosphaera marsilii	0	0	0	0	0	0	0	0	0	0	0

Appendix B2

Calcareous nannoplankton counts for austral summer 1994

Filter diameter (mm)											
No. of SEM screens											
Dims. of screens (microns)											
Area of filter (mm2)											
Area of SEM screens (mm2)											
Screens per filter											
Sample	HC007 - 35m	HC007 - 62m	HC007 - 117m	HC007 -172m	HC007 -227m	HC009 -14m	HC009 -29m	HC009 -55m	HC009 -109m	HC009 -164m	HC009 -217m
Coccospheres / 400 screens:											
Acanthoica quattrospina	0	0	0	0	0	1	1	3	0	0	0
Alisphaera unicornis	0	0	0	0	0	7	0	0	0	0	0
Calcidiscus leptoporus	5	1	9	1	0	0	0	0	0	0	0
Calciopappus rigidus	0	0	0	0	0	0	0	0	0	0	0
Calciosolenia murrayi	0	0	0	0	0	3	5	7	2	0	0
Calicasphaera diconstricta	0	0	0	0	0	4	0	0	0	0	0
Calyptrolithophora papillifera	0	0	0	0	0	0	0	0	0	0	0
Corisphaera gracilis	0	0	0	0	0	0	2	0	0	0	0
Coronosphaera mediterranea	0	0	0	0	0	0	0	0	0	0	0
Cyrtosphaera cucullata	0	0	0	0	7	0	0	0	0	0	0
Discosphaera tubifera	0	0	0	0	0	0	2	0	0	0	0
Emiliania huxleyi - cold	114	119	65	9	1	2	0	0	1	2	1
Emiliania huxleyi - warm	3	4	1	2	0	12	24	8	11	9	8
Emiliania huxleyi - polar	4	0	0	0	0	0	0	0	0	0	0
Gephyrocapsa ericsonii	0	0	0	0	0	0	1	0	0	0	0
Gephyrocapsa muellerae	0	0	0	0	0	0	0	2	0	0	0
Helicosphaera carteri	0	0	0	1	0	0	0	2	0	0	0
Holococcolithophorid sp.	3	0	0	0	0	0	0	0	0	0	0
Michaelsarsia elegans	0	0	0	0	0	0	0	0	0	0	0
Ophiaster hydroideus	0	2	0	0	0	0	1	2	2	0	0
Pappomonas weddellensis	0	0	0	0	0	0	0	0	0	0	0
Papposphaera sagittifera	0	0	0	0	0	0	0	0	0	0	0
Papposphaera lepida	0	0	0	0	0	0	0	0	0	0	0
Polycrater galapagensis	0	0	0	0	0	0	0	0	0	0	0
Sphaerocalyptra quadridentata	0	0	0	0	0	0	0	0	0	0	0
Syracosphaera anthos	0	1	0	0	0	0	0	0	2	0	0
Syracosphaera corolla	0	1	0	0	0	0	0	0	0	0	0
Syracosphaera halldalii	0	3	0	0	0	1	12	5	0	0	0
Syracosphaera histrica	0	0	0	0	0	0	0	1	0	0	0
Syracosphaera molischii	3	0	0	0	0	2	0	0	0	0	0
Syracosphaera nana	2	3	4	0	0	7	8	0	0	0	0
Syracosphaera nodosa	3	0	0	0	0	2	0	3	0	0	0
Syracosphaera ossa	0	0	0	0	0	0	0	0	0	0	0
Syracosphaera pulchra	1	0	0	0	0	0	5	0	0	0	0
Syracosphaera rotula	0	0	0	0	0	0	0	0	0	0	0
Syracosphaera sp.	0	0	0	0	0	0	0	0	0	0	0
Umbellosphaera tenuis	0	0	0	0	0	1	2	0	0	0	0
Zygosphaera hellenica	0	0	0	0	0	1	3	1	1	0	0
Zygosphaera marsilii	0	0	0	0	0	0	1	0	0	0	0

Appendix B2

Calcareous nannoplankton counts for austral summer 1994

Sample	HC001 -12m	HC001 -56m	HC001 -110m	HC001 -164m	HC001 - 218m	HC002 -14m	HC002 -28m	HC002 -55m	HC002 -110m	HC002 -163m	HC004 -17m	HC004 -34m
Volume of filtrate:	6	8	8.14	6	6	3	3	6	6	7	3	3
Coccospheres per litre:												
Acanthoica quattrospina	316	474	0	0	316	0	0	0	0	271	5059	3162
Alisphaera unicornis	0	0	0	0	0	0	0	0	0	0	0	0
Calcidiscus leptoporus	0	474	233	316	0	0	0	316	316	0	3162	0
Calciopappus rigidus	0	237	0	0	0	0	0	0	0	0	0	0
Calciosolenia murrayi	0	0	0	0	0	1265	1897	0	0	0	4427	2529
Calicasphaera diconstricta	0	0	0	0	0	0	0	0	0	0	0	0
Calyptrolithophora papillifera	316	0	0	0	0	0	0	0	0	0	0	0
Corisphaera gracilis	0	0	0	0	0	0	0	0	0	0	0	0
Coronosphaera mediterranea	632	0	0	0	949	1265	632	1265	316	0	0	2529
Cyrtosphaera cucullata	0	0	0	0	0	0	0	0	0	0	0	47427
Discosphaera tubifera	0	0	0	0	0	0	0	0	0	0	0	0
Emiliania huxleyi - cold	11383	107186	9555	6640	13280	18339	12647	13912	4427	5691	49325	38574
Emiliania huxleyi - warm	13912	86318	1631	2529	16758	34780	23398	45214	18339	35774	58810	0
Emiliania huxleyi - polar	0	0	0	0	0	0	0	0	0	0	0	0
Gephyrocapsa ericsonii	0	0	0	0	0	0	0	0	0	0	0	0
Gephyrocapsa muellerae	632	4980	1398	316	316	1265	0	1265	0	0	632	632
Helicosphaera carteri	0	0	0	0	0	0	0	0	949	0	0	0
Holococcolithophorid sp.	1265	0	233	0	0	0	0	0	0	0	0	0
Michaelsarsia elegans	0	0	0	0	0	0	0	0	316	0	0	632
Ophiaster hydroideus	0	474	0	0	0	0	0	632	0	0	0	0
Pappomonas weddellensis	0	0	0	0	0	0	0	0	0	0	0	632
Papposphaera sagittifera	0	0	0	0	0	0	0	0	0	0	0	0
Papposphaera lepida	0	0	0	0	0	0	0	0	0	0	0	1897
Polycrater galapagensis	0	0	0	0	0	0	0	0	0	0	0	0
Sphaerocalyptra quadridentata	0	0	0	0	0	0	0	0	0	0	0	0
Syracosphaera anthos	0	0	0	0	0	0	0	0	0	0	0	0
Syracosphaera corolla	1581	0	0	0	316	0	1897	632	0	0	632	0
Syracosphaera halldalii	0	0	0	0	0	0	0	0	0	0	0	0
Syracosphaera histrica	632	0	0	0	0	0	0	0	0	0	0	0
Syracosphaera molischii	4427	949	233	949	632	3794	3162	949	949	542	2529	3794
Syracosphaera nana	0	0	0	0	0	0	0	0	0	0	0	0
Syracosphaera nodosa	1265	711	0	0	949	2529	4427	1265	0	271	8221	3794
Syracosphaera ossa	0	474	0	0	0	0	0	0	0	0	0	0
Syracosphaera pulchra	0	711	0	632	632	0	1897	316	1265	1084	1897	0
Syracosphaera rotula	0	474	0	0	0	0	0	0	0	0	0	0
Syracosphaera sp.	632	1186	0	0	949	0	0	316	632	0	1897	632
Umbellosphaera tenuis	12963	3557	0	0	12015	17706	0	632	0	0	1897	1897
Zygosphaera hellenica	0	0	0	0	0	0	0	0	0	0	0	0
Zygosphaera marsilii	0	0	0	0	0	0	0	0	0	0	0	0
Total coccospheres/litre:	49957	208206	13284	11383	47111	80943	49957	66715	27508	43633	138488	108135

Appendix B2

Calcareous nannoplankton counts for austral summer 1994

Sample	HC004 -62m	HC004 -120m	HC004 -180m	HC004 -240m	HC005 -19m	HC005 -35m	HC005 - 62m	HC005 -117m	HC005 -172m	HC005 -227m	HC007 -19m
Volume of filtrate:	6	6.75	6	6	3	3	6	6	7	6	2
Coccospheres per litre:											
Acanthoica quattrospina	316	0	0	0	1897	3162	1581	0	0	0	0
Alisphaera unicornis	0	0	0	0	0	0	0	0	0	0	0
Calcidiscus leptoporus	2529	281	0	0	0	632	0	949	542	0	4743
Calciopappus rigidus	316	0	0	0	0	0	316	0	0	0	0
Calciosolenia murrayi	949	0	0	0	0	632	316	0	0	0	0
Calicasphaera diconstricta	0	0	0	0	0	0	0	0	0	0	0
Calyptrolithophora papillifera	0	0	0	0	0	0	0	0	0	0	0
Corisphaera gracilis	0	0	0	0	0	0	0	0	0	0	0
Coronosphaera mediterranea	0	0	0	0	0	0	0	0	0	0	0
Cyrtosphaera cucullata	0	0	0	0	1897	1897	0	0	0	0	0
Discosphaera tubifera	0	0	0	0	0	0	0	0	0	0	0
Emiliania huxleyi - cold	71457	17144	1265	1897	38574	30986	15809	13596	4336	3162	90112
Emiliania huxleyi - warm	74303	22765	4743	3794	20236	14544	8537	5059	4065	1265	5691
Emiliania huxleyi - polar	0	0	0	0	0	0	0	0	0	1897	10434
Gephyrocapsa ericsonii	0	0	0	0	0	0	0	0	0	0	0
Gephyrocapsa muellerae	949	0	0	0	0	0	0	0	0	0	0
Helicosphaera carteri	0	0	0	0	0	0	0	0	0	0	0
Holococcolithophorid sp.	0	0	0	0	3162	1265	632	0	0	0	0
Michaelsarsia elegans	632	0	0	0	0	2529	0	0	0	0	0
Ophiaster hydroideus	0	0	0	0	0	0	2529	0	0	0	0
Pappomonas weddellensis	0	281	0	0	0	0	0	0	0	0	0
Papposphaera sagittifera	0	0	0	0	1265	0	0	0	0	0	0
Papposphaera lepida	0	0	0	0	0	0	0	0	0	0	0
Polycrater galapagensis	0	0	0	0	0	0	316	0	0	0	0
Sphaerocalyptra quadridentata	0	0	0	0	0	0	316	0	0	0	0
Syracosphaera anthos	316	0	0	0	0	0	0	0	0	0	0
Syracosphaera corolla	316	0	0	0	3162	3162	632	316	0	0	0
Syracosphaera halldalii	0	0	0	0	632	2529	632	0	0	0	0
Syracosphaera histrica	0	0	0	0	0	0	0	316	0	0	0
Syracosphaera molischii	7272	0	316	0	4427	6324	1581	0	542	0	1897
Syracosphaera nana	0	0	0	0	0	0	0	0	0	0	0
Syracosphaera nodosa	0	0	316	0	6324	8853	3162	316	0	0	3794
Syracosphaera ossa	0	0	0	0	0	0	316	0	0	0	0
Syracosphaera pulchra	0	281	316	316	1897	1897	316	1265	0	0	949
Syracosphaera rotula	0	0	0	0	0	0	0	0	0	0	0
Syracosphaera sp.	632	0	0	0	0	0	1265	0	271	0	0
Umbellosphaera tenuis	632	0	0	0	3162	1265	316	0	0	0	0
Zygosphaera hellenica	0	0	0	0	0	0	0	0	0	0	0
Zygosphaera marsilii	0	0	0	0	0	0	0	0	0	0	0
Total coccospheres/litre:	160621	40752	6956	6007	86634	79678	38574	21817	9756	6324	117620

Appendix B2

Calcareous nannoplankton counts for austral summer 1994

Sample	HC007 - 35m	HC007 - 62m	HC007 - 117m	HC007 -172m	HC007 -227m	HC009 -14m	HC009 -29m	HC009 -55m	HC009 -109m	HC009 -164m	HC009 -217m
Volume of filtrate:	4.5	4	4	4	5	3	3	3	5	5	5
Coccospheres per litre:											
Acanthoica quattrospina	0	0	0	0	0	632	632	1897	0	0	0
Alisphaera unicornis	0	0	0	0	0	4427	0	0	0	0	0
Calcidiscus leptoporus	2108	474	4268	474	0	0	0	0	0	0	0
Calciopappus rigidus	0	0	0	0	0	0	0	0	0	0	0
Calciosolenia murrayi	0	0	0	0	0	1897	3162	4427	759	0	0
Calicasphaera diconstricta	0	0	0	0	0	2529	0	0	0	0	0
Calyptrolithophora papillifera	0	0	0	0	0	0	0	0	0	0	0
Corisphaera gracilis	0	0	0	0	0	0	1265	0	0	0	0
Coronosphaera mediterranea	0	0	0	0	0	0	0	0	0	0	0
Cyrtosphaera cucullata	0	0	0	0	2656	0	0	0	0	0	0
Discosphaera tubifera	0	0	0	0	0	0	1265	0	0	0	0
Emiliania huxleyi - cold	48060	56439	30828	4268	379	1265	0	0	379	759	379
Emiliania huxleyi - warm	1265	1897	474	949	0	7588	15177	5059	4174	3415	3035
Emiliania huxleyi - polar	1686	0	0	0	0	0	0	0	0	0	0
Gephyrocapsa ericsonii	0	0	0	0	0	0	632	0	0	0	0
Gephyrocapsa muellerae	0	0	0	0	0	0	0	1265	0	0	0
Helicosphaera carteri	0	0	0	474	0	0	0	1265	0	0	0
Holococcolithophorid sp.	1265	0	0	0	0	0	0	0	0	0	0
Michaelsarsia elegans	0	0	0	0	0	0	0	0	0	0	0
Ophiaster hydroideus	0	949	0	0	0	0	632	1265	759	0	0
Pappomonas weddellensis	0	0	0	0	0	0	0	0	0	0	0
Papposphaera sagittifera	0	0	0	0	0	0	0	0	0	0	0
Papposphaera lepida	0	0	0	0	0	0	0	0	0	0	0
Polycrater galapagensis	0	0	0	0	0	0	0	0	0	0	0
Sphaerocalyptra quadridentata	0	0	0	0	0	0	0	0	0	0	0
Syracosphaera anthos	0	474	0	0	0	0	0	0	759	0	0
Syracosphaera corolla	0	474	0	0	0	0	0	0	0	0	0
Syracosphaera halldalii	0	1423	0	0	0	632	7588	3162	0	0	0
Syracosphaera histrica	0	0	0	0	0	0	0	632	0	0	0
Syracosphaera molischii	1265	0	0	0	0	1265	0	0	0	0	0
Syracosphaera nana	843	1423	1897	0	0	4427	5059	0	0	0	0
Syracosphaera nodosa	1265	0	0	0	0	1265	0	1897	0	0	0
Syracosphaera ossa	0	0	0	0	0	0	0	0	0	0	0
Syracosphaera pulchra	422	0	0	0	0	0	3162	0	0	0	0
Syracosphaera rotula	0	0	0	0	0	0	0	0	0	0	0
Syracosphaera sp.	0	0	0	0	0	0	0	0	0	0	0
Umbellosphaera tenuis	0	0	0	0	0	632	1265	0	0	0	0
Zygosphaera hellenica	0	0	0	0	0	632	1897	632	379	0	0
Zygosphaera marsilii	0	0	0	0	0	0	632	0	0	0	0
Total coccospheres/litre:	58178	63553	37468	6166	3035	27192	42368	21500	7209	4174	3415

Appendix B2

Calcareous nannoplankton counts for austral summer 1994

Sample	HC001 -12m	HC001 -56m	HC001 -110m	HC001 -164m	HC001 - 218m	HC002 -14m	HC002 -28m	HC002 -55m	HC002 -110m	HC002 -163m	HC004 -17m	HC004 -34m
%species of total coccospheres												
Acanthoica quattrospina	0.63%	0.23%	0.00%	0.00%	0.67%	0.00%	0.00%	0.00%	0.00%	0.62%	3.65%	2.92%
Alisphaera unicornis	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Calcidiscus leptoporus	0.00%	0.23%	1.75%	2.78%	0.00%	0.00%	0.00%	0.47%	1.15%	0.00%	2.28%	0.00%
Calciopappus rigidus	0.00%	0.11%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Calciosolenia murrayi	0.00%	0.00%	0.00%	0.00%	0.00%	1.56%	3.80%	0.00%	0.00%	0.00%	3.20%	2.34%
Calicasphaera diconstricta	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Calyptrolithophora papillifera	0.63%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Corisphaera gracilis	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Coronosphaera mediterranea	1.27%	0.00%	0.00%	0.00%	2.01%	1.56%	1.27%	1.90%	1.15%	0.00%	0.00%	2.34%
Cyrtosphaera cucullata	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	43.86%
Discosphaera tubifera	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Emiliania huxleyi - cold	22.78%	51.48%	71.93%	58.33%	28.19%	22.66%	25.32%	20.85%	16.09%	13.04%	35.62%	35.67%
Emiliania huxleyi - warm	27.85%	41.46%	12.28%	22.22%	35.57%	42.97%	46.84%	67.77%	66.67%	81.99%	42.47%	0.00%
Emiliania huxleyi - polar	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Gephyrocapsa ericsonii	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Gephyrocapsa muellerae	1.27%	2.39%	10.53%	2.78%	0.67%	1.56%	0.00%	1.90%	0.00%	0.00%	0.46%	0.58%
Helicosphaera carteri	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	3.45%	0.00%	0.00%	0.00%
Holococcolithophorid sp.	2.53%	0.00%	1.75%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Michaelsarsia elegans	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	1.15%	0.00%	0.00%	0.58%
Ophiaster hydroideus	0.00%	0.23%	0.00%	0.00%	0.00%	0.00%	0.00%	0.95%	0.00%	0.00%	0.00%	0.00%
Pappomonas weddellensis	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.58%
Papposphaera sagittifera	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Papposphaera lepida	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	1.75%
Polycrater galapagensis	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Sphaerocalyptra quadridentata	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Syracosphaera anthos	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Syracosphaera corolla	3.16%	0.00%	0.00%	0.00%	0.67%	0.00%	3.80%	0.95%	0.00%	0.00%	0.46%	0.00%
Syracosphaera halldalii	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Syracosphaera histrica	1.27%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Syracosphaera molischii	8.86%	0.46%	1.75%	8.33%	1.34%	4.69%	6.33%	1.42%	3.45%	1.24%	1.83%	3.51%
Syracosphaera nana	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Syracosphaera nodosa	2.53%	0.34%	0.00%	0.00%	2.01%	3.13%	8.86%	1.90%	0.00%	0.62%	5.94%	3.51%
Syracosphaera ossa	0.00%	0.23%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Syracosphaera pulchra	0.00%	0.34%	0.00%	5.56%	1.34%	0.00%	3.80%	0.47%	4.60%	2.48%	1.37%	0.00%
Syracosphaera rotula	0.00%	0.23%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Syracosphaera sp.	1.27%	0.57%	0.00%	0.00%	2.01%	0.00%	0.00%	0.47%	2.30%	0.00%	1.37%	0.58%
Umbellosphaera tenuis	25.95%	1.71%	0.00%	0.00%	25.50%	21.88%	0.00%	0.95%	0.00%	0.00%	1.37%	1.75%
Zygosphaera hellenica	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Zygosphaera marsilii	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

Appendix B2

Calcareous nannoplankton counts for austral summer 1994

Sample	HC004 -62m	HC004 -120m	HC004 -180m	HC004 -240m	HC005 -19m	HC005 -35m	HC005 - 62m	HC005 -117m	HC005 -172m	HC005 -227m	HC007 -19m
%species of total coccospheres											
Acanthoica quattrospina	0.20%	0.00%	0.00%	0.00%	2.19%	3.97%	4.10%	0.00%	0.00%	0.00%	0.00%
Alisphaera unicornis	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Calcidiscus leptoporus	1.57%	0.69%	0.00%	0.00%	0.00%	0.79%	0.00%	4.35%	5.56%	0.00%	4.03%
Calciopappus rigidus	0.20%	0.00%	0.00%	0.00%	0.00%	0.00%	0.82%	0.00%	0.00%	0.00%	0.00%
Calciosolenia murrayi	0.59%	0.00%	0.00%	0.00%	0.00%	0.79%	0.82%	0.00%	0.00%	0.00%	0.00%
Calicasphaera diconstricta	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Calyptrolithophora papillifera	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Corisphaera gracilis	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Coronosphaera mediterranea	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Cyrtosphaera cucullata	0.00%	0.00%	0.00%	0.00%	2.19%	2.38%	0.00%	0.00%	0.00%	0.00%	0.00%
Discosphaera tubifera	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Emiliania huxleyi - cold	44.49%	42.07%	18.18%	31.58%	44.53%	38.89%	40.98%	62.32%	44.44%	50.00%	76.61%
Emiliania huxleyi - warm	46.26%	55.86%	68.18%	63.16%	23.36%	18.25%	22.13%	23.19%	41.67%	20.00%	4.84%
Emiliania huxleyi - polar	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	30.00%	8.87%
Gephyrocapsa ericsonii	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Gephyrocapsa muellerae	0.59%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Helicosphaera carteri	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Holococcolithophorid sp.	0.00%	0.00%	0.00%	0.00%	3.65%	1.59%	1.64%	0.00%	0.00%	0.00%	0.00%
Michaelsarsia elegans	0.39%	0.00%	0.00%	0.00%	0.00%	3.17%	0.00%	0.00%	0.00%	0.00%	0.00%
Ophiaster hydroideus	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	6.56%	0.00%	0.00%	0.00%	0.00%
Pappomonas weddellensis	0.00%	0.69%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Papposphaera sagittifera	0.00%	0.00%	0.00%	0.00%	1.46%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Papposphaera lepida	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Polycrater galapagensis	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.82%	0.00%	0.00%	0.00%	0.00%
Sphaerocalyptra quadridentata	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.82%	0.00%	0.00%	0.00%	0.00%
Syracosphaera anthos	0.20%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Syracosphaera corolla	0.20%	0.00%	0.00%	0.00%	3.65%	3.97%	1.64%	1.45%	0.00%	0.00%	0.00%
Syracosphaera halldalii	0.00%	0.00%	0.00%	0.00%	0.73%	3.17%	1.64%	0.00%	0.00%	0.00%	0.00%
Syracosphaera histrica	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	1.45%	0.00%	0.00%	0.00%
Syracosphaera molischii	4.53%	0.00%	4.55%	0.00%	5.11%	7.94%	4.10%	0.00%	5.56%	0.00%	1.61%
Syracosphaera nana	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Syracosphaera nodosa	0.00%	0.00%	4.55%	0.00%	7.30%	11.11%	8.20%	1.45%	0.00%	0.00%	3.23%
Syracosphaera ossa	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.82%	0.00%	0.00%	0.00%	0.00%
Syracosphaera pulchra	0.00%	0.69%	4.55%	5.26%	2.19%	2.38%	0.82%	5.80%	0.00%	0.00%	0.81%
Syracosphaera rotula	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Syracosphaera sp.	0.39%	0.00%	0.00%	0.00%	0.00%	0.00%	3.28%	0.00%	2.78%	0.00%	0.00%
Umbellosphaera tenuis	0.39%	0.00%	0.00%	0.00%	3.65%	1.59%	0.82%	0.00%	0.00%	0.00%	0.00%
Zygosphaera hellenica	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Zygosphaera marsilii	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

Appendix B2

Calcareous nannoplankton counts for austral summer 1994

Sample	HC007 - 35m	HC007 - 62m	HC007 - 117m	HC007 -172m	HC007 -227m	HC009 -14m	HC009 -29m	HC009 -55m	HC009 -109m	HC009 -164m	HC009 -217m
%species of total coccosphres											
Acanthoica quattrospina	0.00%	0.00%	0.00%	0.00%	0.00%	2.33%	1.49%	8.82%	0.00%	0.00%	0.00%
Alisphaera unicornis	0.00%	0.00%	0.00%	0.00%	0.00%	16.28%	0.00%	0.00%	0.00%	0.00%	0.00%
Calcidiscus leptoporus	3.62%	0.75%	11.39%	7.69%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Calciopappus rigidus	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Calciosolenia murrayi	0.00%	0.00%	0.00%	0.00%	0.00%	6.98%	7.46%	20.59%	10.53%	0.00%	0.00%
Calicasphaera diconstricta	0.00%	0.00%	0.00%	0.00%	0.00%	9.30%	0.00%	0.00%	0.00%	0.00%	0.00%
Calyptrolithophora papillifera	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Corisphaera gracilis	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	2.99%	0.00%	0.00%	0.00%	0.00%
Coronosphaera mediterranea	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Cyrtosphaera cucullata	0.00%	0.00%	0.00%	0.00%	87.50%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Discosphaera tubifera	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	2.99%	0.00%	0.00%	0.00%	0.00%
Emiliania huxleyi - cold	82.61%	88.81%	82.28%	69.23%	12.50%	4.65%	0.00%	0.00%	5.26%	18.18%	11.11%
Emiliania huxleyi - warm	2.17%	2.99%	1.27%	15.38%	0.00%	27.91%	35.82%	23.53%	57.89%	81.82%	88.89%
Emiliania huxleyi - polar	2.90%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Gephyrocapsa ericsonii	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	1.49%	0.00%	0.00%	0.00%	0.00%
Gephyrocapsa muellerae	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	5.88%	0.00%	0.00%	0.00%
Helicosphaera carteri	0.00%	0.00%	0.00%	7.69%	0.00%	0.00%	0.00%	5.88%	0.00%	0.00%	0.00%
Holococcolithophorid sp.	2.17%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Michaelsarsia elegans	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Ophiaster hydroideus	0.00%	1.49%	0.00%	0.00%	0.00%	0.00%	1.49%	5.88%	10.53%	0.00%	0.00%
Pappomonas weddellensis	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Papposphaera sagittifera	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Papposphaera lepida	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Polycrater galapagensis	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Sphaerocalyptra quadridentata	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Syracosphaera anthos	0.00%	0.75%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	10.53%	0.00%	0.00%
Syracosphaera corolla	0.00%	0.75%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Syracosphaera halldalii	0.00%	2.24%	0.00%	0.00%	0.00%	2.33%	17.91%	14.71%	0.00%	0.00%	0.00%
Syracosphaera histrica	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	2.94%	0.00%	0.00%	0.00%
Syracosphaera molischii	2.17%	0.00%	0.00%	0.00%	0.00%	4.65%	0.00%	0.00%	0.00%	0.00%	0.00%
Syracosphaera nana	1.45%	2.24%	5.06%	0.00%	0.00%	16.28%	11.94%	0.00%	0.00%	0.00%	0.00%
Syracosphaera nodosa	2.17%	0.00%	0.00%	0.00%	0.00%	4.65%	0.00%	8.82%	0.00%	0.00%	0.00%
Syracosphaera ossa	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Syracosphaera pulchra	0.72%	0.00%	0.00%	0.00%	0.00%	0.00%	7.46%	0.00%	0.00%	0.00%	0.00%
Syracosphaera rotula	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Syracosphaera sp.	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Umbellosphaera tenuis	0.00%	0.00%	0.00%	0.00%	0.00%	2.33%	2.99%	0.00%	0.00%	0.00%	0.00%
Zygosphaera hellenica	0.00%	0.00%	0.00%	0.00%	0.00%	2.33%	4.48%	2.94%	5.26%	0.00%	0.00%
Zygosphaera marsilii	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	1.49%	0.00%	0.00%	0.00%	0.00%

Appendix B3

Measurements for *E. huxleyi* coccoliths, austral summer 1994.

Station no.	Depth	Shape of Coccosphere	Size of Coccosphere (μm)	Size of Coccolith length of long axis (μm)	Coccolith Symmetry	Number of 'T' elements on distal shield	Thickness of 'T' elements	Central Area Structure	Central Area Measurement long axis (μm)	Relief (elevation of distal shield)	Central area Structure (open/closed)
CTD 16	10m	circular to elliptical	7.5, 6, 5	2.8, 3, 2.1, 3.8	round to eliptical for type Z	28, 32, 29, 33, 34	mostly thin a few thick	open/ overgrowth for thick ones	1.2, 1.5, 2, 1.3	high	open to closed lath-like
	25m	circular to elliptical	6.5, 7, 7, 7, 8, 8	3, 3.1, 3.1, 2.5, 3,3, 2.8, 3.1, 3.2	round	27, 29, 28, 32, 29, 32, 29, 29, 27,	all thin	open	1, 1.2, 1, 1.2, 1, 1.2, 1, 1.	high	closed lath-like, a few open
	50m	round	5.1, 7, 5.6, 5	3.1, 2.9, 3, 3.1	round to elliptical	28, 30, 30, 27	mostly thin a few thick	open	1.2, 1.3, 1, 1.2.	high	lath-like or open
	100m	round	5.1	3, 3.7, 2.9	elliptical	33, 26, 33, 37	all thin	open	1.2, 1, 1, 1.1, 1.1	high	lath-like to open
	150m	round to elliptical	6.5	3.5, 3.5.	round to elliptical	31, 30, 35	all thin	open	1.2, 1.8	high	eroded lath-like
CTD 21	10m	round	6,7,6	3.1, 3, 3.1,3.5, 2.1, 3.1.	round to elliptical	28, 32, 28, 28, 29, 26, 26	all thin	mostly open some with overgrowth	1.5, 1.3, 1.2	high	lath-like to eroded
	25m	round	7, 5, 8, 6.2, 6 10	2.8, 2.8, 2.3, 3.	round to elliptical	28, 26, 36, 29, 35	all thin	open	1.1, 1, 1.1, 1, 1.2, 1, 1.1, 1 1, 1.	high	lath-like to eroded
	50m	round	6, 7.5, 5.5, 5.5.	3, 2, 3, 4.1, 3.1, 4, 3	round to elliptical	36, 29, 29, 29, 31.	all thin	open	1.1, 1, 1.1, 1, 1.1, 1.1, 1.3, 0.8.	high	lath-like to eroded
	100m	round			round to elliptical		all thin	open			
	150m	round to elliptical	8, 5.1, 4.5, 6.5.	2.5, 3, 2.2, 2.5, 3, 3.1, 2.9.	round to elliptical	33, 30, 25, 29, 33, 30.	Thicker but not 'thick'	open	1, 1, 1, 1.1, 1.2, 1.5.	high	open
CTD 30	10m	round	5, 5.5	2, 2.5, 2.9 2.5	round to elliptical	25, 29, 26, 27, 23.	all thin	open	1, 1.1, 1.1, 1, 1.	high	thin lath-like to open
	50m	round	6, 6.1, 6, 6.	3, 3.5, 2.9, 3.1, 3.	round to elliptical	27, 26, 29, 34.	all thin	open	1.1,1.1, 1, 1, 1.1, 1, 1.1.	high	thin lath-like to open
	75m	round	5	2.9, 2.9, 2.5, 2.9.	round to elliptical	26, 25, 22, 19, 23.	all thin	open	1.1, 1.1, 1, 0.9, 0.9, 0.9, 0.7, 1.	high	thin lath-loke to open
	100m	round	5.1, 4.5, 4	2.8, 3, 3.2, 2.5, 2.5, 2.5, 1.4, 2.5	round to elliptical	37, 25, 20, 34	all thin	open	1.1, 0.9, 1.1, 0.8, 0.9, 1	high	thin lath-like to open
	150m	round	5	1, 1, 0.9, 0.9, 2.8, 2.3, 2.9, 2.9	round to elliptical	29, 25, 21, 22	All thin	open	1, 1, 0.9,1, 0.9, 0.9.	high	thin lath-like to open

Appendix B3

Measurements for *E. huxleyi* coccoliths, austral summer 1994.

Station no.	Depth	Shape of Coccosphere	Size of Coccosphere (µm)	Size of Coccolith length of long axis (µm)	Coccolith Symmetry	Number of 'T' elements on distal shield	Thickness of 'T' elements	Central Area Structure	Central Area Measurement long axis (µm)	Relief (elevation of distal shield)	Central area Structure (open/closed)
CTD 37	10m	mostly round to irregular	8, 5.5, 6, 4.5	2.8, 3.1, 2.5, 2.1	round to elliptical	25, 27, 28, 29, 26	All thin	open	1, 1. 1, 1, 1.1 1.1, 1, 1	high	thin lath-like to open
	50m	round	5.1	3, 2.2, 2.5	round to elliptical	28, 25, 25	All thin	open	1.1, 0.9, 1	high	thin lath-like to open
	100m	round	5.9	3, 2.2, 2.5	round to elliptical	27, 23, 25, 31, 27	All thin	open	1, 0.9, 1	high	thin lath-like to open
	150m	round	5, 5.5,6,5 5.1,5	3, 3, 3.3 2.9,2.5,2.5	round to elliptical	26, 30, 29, 29,27,31,24	All thin	open	1, 1.1, 1.3 1,1.1,1, 1.2	high	thin lath-like to open
CTD 39	10m	round	5.5,5.5,4.5,9	3,3.2.9,2.8 2.8,3.5,2,3.5	round to elliptical	23,26,26,21	all thin	open	1,1,1.1,1,1, 1,1	?high	open to closed with lath-like
	60m	round	6,6,6,6.1	3,2.8,3, 2.8 3,2.8	round to elliptical	31,26,27,28 25,21, 26,25	all thin	open	0.9,1,1.1,0.9 1,1.2	?high	open
	100m	round	6,5.1,5.7,5.1	3.5,3.1,3,2.1 2.5,2.5,3.5	round to elliptical	28,28,20,25 30,29	all thin	open	0.8,1.1,0.8,1 1.1,0.9,1,1.1	?high ?high	open to closed with lath-like
CTD 43	10m	round	5, 6.7, 6.1	3, 3.5, 4, 3.5 2.9	round to elliptical	32, 33, 26, 26	all thin	open	1.2, 1.6, 1, 1.1, 1	high	closed lath-like to open
	40m	round	4.7, 5	2.8, 2.8, 3.1 3.1, 3.1, 3.1	round to elliptical	28,26, 27, 26, 24, 24	all thin	open	1, 1.1,1.1 1,1,1.1	?high	open to closed and lath-like
	125m	round	5.1,5.3,6.1 6.8	4,2.5,3.1,4 2.9	round to elliptical	27,30,29,27	all thin	open	0.9,1.2,1,1.3 1.2	?high	open to closed and lath-like
CTD 47	10m	round	4.9, 5, 5.5 5.5	2.5, 2.5, 3 2.5, 2.9	round to elliptical	30, 23, 25, 23	all thin		1, 1.1, 1, 1.1 1, 0.8, 1.1	high	thin lath-like
	40m	round	5.4	3, 3.1, 3, 3.1 4.2	round to elliptical	26, 21, 21, 31	all thin	partial on a few	1.1, 1.1, 1, 1, 1.6, 2	high	thin lath-like to open
	125m	round	4, 5.1um	3, 2.2, 3 3.1, 2.5	round to elliptical	31, 32, 23 24	all thin	open	1, 1.1, 1.1,1 1	high	thin lath-like
	180m	round	5.1, 5.2, 4, 6, 5.8	3, 3.9, 3.9 2.9, 2.5	round to elliptical	28, 24, 22, 22, 26	all thin	open	1, 1, 0.9, 1	high	thin lath-like
CTD 51	10m	round	6.2	3, 3, 3.1	round to elliptical	28, 30,32	all thin	open	1, 1, 1.1 1.2	high	open to lath-like
	50m	round to elliptical	6, 6.1, 6.5	3.1, 4, 3, 3.1	round to elliptical	30, 24, 31, 29, 27	all thin	open	1, 1, 1.1,1, 1.1, 1, 1.1	high	open to thin lath-like
	100m	round	5.5, 5.5,6	3, 3, 3.5,4 3.5, 3.5,4	round to elliptical	24, 30,27, 32,	all thin	open	1.5, 1, 1.1,1 1, 1.1, 1.1	high	open to thin lath-like

Appendix B3

Measurements for *E. huxleyi* coccoliths, austral summer 1994.

Station no.	Depth	Shape of Coccosphere	Size of Coccosphere (µm)	Size of Coccolith length of long axis (µm)	Coccolith Symmetry	Number of 'T' elements on distal shield	Thickness of 'T' elements	Central Area Structure	Central Area Measurement long axis (µm)	Relief (elevation of distal shield)	Central area Structure (open/closed)
CTD 54	10m	round	6, 7, 5.2	3.3, 3, 4.1, 3 3.2, 2.9, 2.9 2.9	round to elliptical	30, 26, 30 28, 29	all thin	open	1.3, 1.1, 2, 1, 1.1, 1, 1, 1	high	thin lath-like to open
	50m	round	6, 7	3, 3, 3.4, 3.2 3	round to elliptical	26, 32, 29 31	all thin	open	1.1, 1, 1.1, 1.2, 1, 1.1	high	mostly all thin lath-like
	100m	round	5.5, 6.5,6,7	3, 3, 3.2,2.9 2.9,3.5	round to elliptical	25, 27, 31, 29,32, 23	all thin	open	1.1, 1, 1, 1.2	high	thin lath-like
	130m		6, 4.1	3, 2.8, 2.3 3.1, 3	round to elliptical	31, 26, 30	all thin	open	1, 1.1, 1.2, 1.1,1.1, 1.1	high	thin lath-like
CTD 59	10m	round	7.5	2.8,3,2.8, 2.5	elliptical	32,28,28	all thin	open	1,1.1,1,1.1	?high	closed with lath-like

Appendix C

Taxonomy

The classification of calcareous nannoplankton remains unclear for many species and is constantly being revised. For example, confusion between the species *G. muellerae* and *G. caribbeanica* has been recognised. Some authors avoid the use of species names for this genus, whereas others consider it to be one species of various morphotypes. The most recent classification of extant species of calcareous nannoplankton (and the one adopted in this text) is the classification outlined by Jordan and Kleijne (1994) and is as follows:

Kingdom:	**Protista** Haeckel, 1866
Division:	**Haptophyta** Cavalier-Smith, 1986
Class:	**Prymenesiophyceae** Hibberd, 1976
Order:	**Coccolithophorales** Schiller 1926

Thirteen families of calcareous nannoplankton are recognised within the order of Coccolithophorales. Each species is identified and named on the basis of the construction of the coccolith. In this text, the current name is used for species when referring to previous work, and therefore may differ from the original classification used by the original authors, e.g., *Umbilicosphaera mirabilis* is now *Umbilicosphaera sibogae*, *Rhabdosphaera stylifera* is now *Rhabdosphaera clavigera*, etc.

Extinct species identified in the sediments are based on the taxonomy outlined in Perch-Nielsen (1985) and were identified using both the electron microscope and the light microscope. Species are listed separately for water column and sediment samples in alphabetical order of Family name.

A. Coccolithophores identified in water samples

1. Heterococcolithophores - coccoliths constructed of crystal elements that differ in size and shape.

Family **Calciosoleniaceae** Kamptner 1937

Calciosolenia murrayi Gran, 1912

Winter and Siesser, 1994, pg. 117 Fig. 3.

Kleijne, 1993, pg. 251, Plate 1, Figs 3, 4, 5 and 6.

Description: Long elongated coccosphere, narrowing at the poles, consisting of diamond-shaped coccoliths. Three or 4 long thin spines protrude from the poles.

Remarks: This species was identified in the water column at stations HC002, HC004, HC005 and HC009 to a depth of 109m.

Family **Coccolithaceae** Poche, 1913

Calcidiscus leptoporus (Murray and Blackman, 1898) Loeblich and Tappan, 1978 f. *leptoporus*

Plate 1, Fig. 8; Plate 2, Fig. 1.

Winter and Siesser, 1994, pg 119, Fig.11C.

Kleijne, 1993, pg. 207, Plate 1, Figs 1-6.

Andruleit, 1995, Table 1, Figs 3a-c.

Hallegraeff, 1984, pg. 232, Fig. 6.

Description: Round coccosphere consisting of overlapping, circular coccoliths. Coccoliths are constructed of two shields with the distal shield divided by regular sutures, with resulting elements dextrally imbricated.

Remarks: This species was identified in the water column at all stations down to the SAF, between the surface and 156m water depth. It is also common in sediment samples. Some variation in size of coccoliths was noted in living individuals with an average size of 3 to 6µm for coccoliths and 15 to 24 elements on the distal shield.

Family **Helicosphaeraceae** Black, 1971, emend. Jafar and Martini, 1975

Helicosphaera carteri (Wallich, 1877) Kamptner, 1954 var. *carteri*

Plate 4, Fig. 7.

Winter and Siesser, 1994, pg. 121, Fig. 23A.
Kleijne, 1993, pg. 250, Plate 1, Figs 7-8.
Andruleit, 1995, Table 3, Figs 4a-b
Hallegraeff, 1984, pg. 235, Figs 19-20.

Description: Sub-circular to oval coccosphere covered in large helicoliths in a spiral arrangement. Coccolilths have an elongated slit in the cental area.

Remarks: This species is readily identified with both light and electron microscopes. It was identified at stations HC002, HC007 and HC009 at the water depths of 110m, 172m an 55m respectively; and CTD 21 at 103m. It is a common component of sediment samples.

Family **Noelaerhabdacea** Jerkovic, 1970

Emiliania huxleyi (Lohmann, 1902) Hay and Mohler, in Hay et al., 1967 var. *huxleyi*

Plate 1, Figs 1, 2, 3, 4 and 7; Plate 4, Figs 1, 5 and 8.

Winter and Siesser, 1994, pg. 118 Fig. 6.
Kleijne, 1993, pg. 250, Plate 1, Figs 10-11.
Andruleit, 1995, Table 3, Figs 1a-h.
Samtleben and Bickert, 1990, Plate 2, Figs 1-3, 7-8.
Hallegraeff, 1984, pg. 234, Figs 8-12.

Description: Coccospheres comprising overlapping sub-circular coccoliths of two shields. The distal shield of the coccolith is constructed of distinct "T"-shaped elements radiating from the central area.

Remarks: Four morphotypes of this species were identified in the water column; 'warm water' form which is heavily calcified and has a central opening with a grill-like structure; 'cold water' form with less calcified with a central area either open or with a lath-

like elements; 'polar' form with "T" elements on distal shield distorted, possibly due to dissolution; and, a severely dissolved form. This species is represented in all water samples and sediment samples.

Gephyrocapsa ericsonii McIntyre and Bé, 1967

Plate 2; Fig. 4.

Winter and Siesser, 1994, pg. 123, Fig. 35.
Kleijne, 1993, pg. 252, Plate 2, Figs 1-2.
Hallegraeff, 1984, pg. 234, Fig. 13.

Description: Small round coccosphere covered in sub-circular coccoliths with well defined central openings covered with a grill-like structure. The central area is spanned by a high relief bridge constructed of two bar elements. Coccoliths are <5μm.

Remarks: Only one coccosphere of this species was identified in the water column at station HC009 at 29m.

Gephyrocapsa muellerae Bréhéret, 1978.

Plate 2; Fig. 5; Plate 4, Fig. 2; Plate 5, Figs 1 and 4.

Winter and Siesser, 1994, pg. 123, Fig. 36.
Kleijne, 1993, pg. 253, Plate 2, Fig. 4.
Andruleit, 1995, Table 3, Figs 3a-c.
Samtleben and Bickert, 1990, Plate 1, Fig. 13.

Description: A medium sized gephyrocapsid with a well defined, oval central opening. Bridge structure is low relief, spanning the central opening at an oblique angle.

Remarks: This species was identified in the water column at all stations for 1995, between the surface and the water depth of 218m. The coccoliths were identified in the sediments using both light and electron microscope with a coccolith size of 3 to 6μm.

Family **Papposphaeraceae** Jordan and Young, 1990

Pappomonas weddellensis Thomsen in Thomsen et al., 1988

Plate 3, Fig. 5.

Thomsen et al., 1988. pg. 430, Figs 32-24.

Description: Semi-calcified coccosphere with rows of sail-like structures at one end.

Remarks: Identified in water column at station HC004 at depths of 34m and 120m.

Papposphaera lepida Tangen, 1972

Winter and Siesser, 1994, pg. 125, Fig. 47.

Description: Semi-calcified coccosphere with raised frilled edges on coccoliths and protruding rods with circular discs at the end.

Remarks: Identified in the water column at station HC004 at a depth of 34m.

Papposphaera obypyramdalis Thomsen in Thomsen et al., 1988

Plate 3, Fig. 4

Thomsen et al., 1988. pg. 432, Figs 38-40.

Description: Semi-calcified coccosphere with rod like structures protruding in upright rows. Semi-circular coccoliths constructed of rod-like structures giving a striated appearance.

Remarks: Identified in water column south of the PF (CTD 54) at a depth of 154m based CTD 47 at 130m, CTD 54 at 103m.

Papposphaera sagittifera Manton, Sutherland and McCully, 1976

Plate 3, Fig. 3.

Thomsen et al., 1988. pg. 428, Figs 35-37.

Winter and Siesser, 1994, pg. 125, Fig. 49.

Description: Semi-calcified coccosphere with forked, rod-like structures protruding from one end.

Remarks: This species is not common in the water column and was identified at stations HC005 at 19m, CTD 47 at 130m and CTD 54 at 103m.

Family **Rhabdosphaeraceae** Ostenfeld, 1899

Acanthoica quattrospina, Lohmann, 1903

Winter and Siesser, 1994, pg. 123, Fig. 36.

Kleijne, 1993, pg. 253, Plate 2, Fig. 4.

Andruleit, 1995, Table 3, Figs 3a-c.

Samtleben and Bickert, 1990, Plate 1, Fig. 13.

Description: Elongated coccosphere of circular coccoliths with radial elements. Rhabdoliths at both poles forming thick spines, with four spines at one end.

Remarks: This species was identified in the water column samples at stations CTD 21 at 14m, HC001 to 218m, HC002 to 163m, HC004 to 62m, HC005 to 62m, HC009 to 55m.

Cyrtosphaera cucullata (Lecal-Schlauder, 1951) Kleijne, 1992

Winter and Siesser, 1994, pg. 130, Fig. 80.

Kleijne, 1993, pg. 156, Plate 3, Figs 1-6.

Description: Coccoliths with protruding domed centres constructed of fine net-like structures covering a sub-circular coccosphere.

Remarks: Identified at station HC005 at 19m and 35m, CTD 16 at 28m and CTD 21 at, CTD 21 at 29m and 53m.

Discosphaera tubifera (Murray and Blackman, 1898) Ostenfeld, 1900

Winter and Siesser, 1994, pg. 130, Fig. 82.

Kleijne, 1993, pg. 164, Plate 7, Figs 5-7.

Hallegraeff, 1984, pg. 238, Figs 34-36.

Description: Coccosphere covered in disc-like coccoliths with large, thick, tubular structures protruding from their centre.

Remarks: Identified at station HC009 only at a depth of 29m.

Family **Syracosphaeraceae** Lemmermann, 1908

Alisphaera unicornis Okada and McIntyre 1977

Winter and Siesser, 1994, pg. 131, Fig. 90A.

Kleijne, 1993, pg. 253, Plate 7, Figs 9-10.

Hallegraeff, 1984, pg. 240, Fig. 41.

Description: Ovoid coccoliths with wide flat brim displaying a thorn like structure at one point, giving the coccosphere a thorny appearance.

Remarks: Identified in the water column at station HC009 at 14m.

Calciopappus rigidus Heimdal in Heimdal and Gaarder, 1981

Winter and Siesser, 1994, pg. 133, Fig. 93.

Kleijne, 1993, pg. 253, Plate 7, Fig. 12.

Description: Elongated, pear-shaped coccosphere covered in ovoid coccoliths with delicate spines protruding from the base. Distinguished from *C. caudatus* by the more rounded shape of the coccoliths.

Remarks: Identified at station HC001, HC004 and H 005, at depths of 56m, 62m respectively; and CTD 16 at 103m and CTD 21 at 103m.

Coronosphaera mediterranea (Lohmann, 1902) Gaarder in Gaarder and Heimdal, 1977

Winter and Siesser, 1994, pg. 133, Fig. 96.

Kleijne, 1993, pg. 255, Plate 3, Figs 2-3.

Hallegraeff, 1984, pg. 241, Fig. 48.

Description: Round coccosphere with coccoliths of ovoid shape. Coccoliths have two flat plates overlapping in the central area which is otherwise constructed of radial rods. The rim of the coccolith is thickened and raised. Some coccoliths at one end have thick short stems protruding.

Remarks: Very similar to *Syracosphaera* spp with the distinction of the thick raised cup-like edges on the coccoliths. This species was identified at stations HC001 at depths of 12m and 218m; HC002 at depths down to 110m, and HC004 at 34m CTD 16 at 53m.

Michaelsarsia elegans Gran 1912 emend. Manton et al., 1984

Winter and Siesser, 1994, pg. 133, Fig. 98.

Kleijne, 1993, pg. 255, Plate 3, Fig. 5.

Description: An oval coccosphere with tightly packed coccoliths. Coccoliths are oval with radiating rods covering the central area. At the base multi-structured 'legs' protrude. These 'legs' appear to be jointed and are constructed of two parrel rods for each section, with a broader, round 'joint' structure at the end of each section.

Remarks: This species was identified in the water column at stations HC002 at 110m; HC004 at 34 and 62m; and, HC005 at 35m,.

Ophiaster hydroideus (Lohmann, 1903) Lohmann, 1913 emend. Manton and Oates, 1983

Winter and Siesser, 1994, pg. 133, Fig. 98.

Kleijne, 1993, pg. 255, Plate 3, Fig. 5.

Description: Round to sub-round coccosphere covered in ovoid coccoliths. Coccoliths are less calcified than *M. elegans* with a thinner rim. The legs protruding from the base of the coccosphere are jointed, with each section forming a solid structures with serrated edges.

Remarks: This species is lightly calcified in comparison to *M. elegans* and was identified at stations CTD 16 at 28m, CTD 21 at 14m, HC001 at 56m, HC002 at 55m, HC005 at 62m, HC007 at 62m and HC009 at 29m, 55m and 109m.

Syracosphaera anthos (Lohmann, 1912) Jordan and Young, 1990

Winter and Siesser, 1994, pg. 134, Fig. 105.

Kleijne, 1993, pg. 261, Plate 2, Fig. 10.

Description: Round coccosphere covered in small ovoid coccoliths. Coccoliths have a slightly raised rim and are covered by rods radiating from the centre. The centre is mostly covered by a plate constructed of overlapping elements. The most distinct feature is the dimorphic endotheca. This is constructed of a second type of coccolith, large, circular, flat with a small, well defined central area.

Remarks: This species was found with associated dimorphic endotheca at stations HC004 at 62m, HC007 at 62m and HC009 at 109m.

Syracosphaera corolla Lecal, 1966

Winter and Siesser, 1994, pg. 135, Fig. 107.

Andruleit, 1995, Table 4, Fig. 2.

Description: Coccosphere with two different types of coccoliths; caneoliths (bowl-shaped, lath-filled area) with distinct striated flange; and large umbelloliths, with broad flanges.

Remarks: This species was identified in water samples at stations HC001 at 12m and 218m, HC002 at 28m and 55m, HC004 at 17m and 62 m, HC005 at 19m, 35m, 62m and 117m, and HC007 at 62m.

Syracosphaera halldalii Gaarder, in Gaarder and Hasle, 1971 f. *halldalii*

Winter and Siesser, 1994, pg. 136, Fig. 111.

Kleijne, 1993, pg. 257, Plate 4, Figs 4-6.

Description: Round coccosphere covered with circular to sub-circular coccoliths. Coccoliths have distinct broad flat distal flange (rim). The central area has a thin, elongated thickened area along the long axis, from which rod structures radiate to the rim.

Remarks: This species was identified at stations HC005 down to 62m, HC007 at 62m and HC009 down to 55m.

Syracosphaera histrica Kamptner, 1941

Winter and Siesser, 1994, pg. 136, Fig. 113.

Kleijne, 1993, pg. 257, Plate 4, Fig. 7.

Description: Round coccosphere covered with ovoid coccoliths. Coccoliths have thickened, slightly raised rim. The centre of the coccoliths has a thick cylindrical protrusion. The central protrusion does not extend much past the rim for most coccoliths but is marginally longer at one end of the coccosphere. Regular rods extend radially from the centre.

Remarks: This species was identified at stations HC001 at 12m, HC005 at 1117m and HC009 at 55m.

Syracosphaera molischii Schiller, 1925

Plate 2, Fig. 8.

Winter and Siesser, 1994, pg. 137, Fig. 115A.

Kleijne, 1993, pg. 255, Plate 3, Figs 10-11.

Andruleit, 1995, Table 4, Figs 5a-c.

Samtleben and Bickert, 1990, Plate 1, Figs 3-4.

Description: Round coccosphere with ovoid coccoliths. Coccoliths have a wide striated rim and the central area is highly ornamented, with the inner edge of the rim often constructed of single rounded structures directed toward the centre. The central area of the coccoliths often show the same single structures.

Remarks: This species was identified at stations HC001 and HC002 at all depths; HC004 down to 180m; HC005 down to 172m; HC007 to 35m; HC009 at 14m; and, CTD 16 at 125m.

Syracosphaera nana (Kamptner, 1941) Okada and McIntyre, 1977

Winter and Siesser, 1994, pg. 137, Fig. 116.

Description: A small coccosphere (~5μm) with covered in ovoid coccoliths. Coccoliths have a solid central area along the long axis, from which radiate regular rod-like structures. The outer rim is thickened and raised slightly. Calcification is light for this species.

Remarks: This species was identified at stations HC007 at depths of 35m, 62m and 117m, and station HC009 at 14m and 29m.

Syracosphaera nodosa Kamptner, 1941

Winter and Siesser, 1994, pg. 138, Fig. 117A.

Kleijne, 1993, pg. 257, Plate 4, Figs 8-9.

Plate 3, Fig. 1.

Description: Round coccosphere covered in elongated coccoliths of oval shape. Coccoliths have a slightly raised rim and are covered by rods radiating from the centre. The centre has a thickened structure along the long axis from which the rods radiate. The

most distinct feature is the dimorphic endotheca. This is constructed of a second type of coccolith, large, circular, flat with a broad outer rim and a central area of overlapping elements, roughly forming a circle. Between the rim and the central area radial rods occupy a small area.

Remarks: This species was found with associated dimorphic endotheca at stations CTD 21 at 14m, HC001 down to 218m, HC002 down to 163m, HC004 to 180m, HC007 to 35m and HC009 to 55m.

Syracosphaera ossa (Lecal, 1966) Loeblich and Tappan, 1968

Winter and Siesser, 1994, pg. 138, Fig. 119.

Kleijne, 1993, pg. 259, Plate 5, Figs 4-5.

Description: Round coccosphere covered in round coccoliths which have pronounced wide flange like rim. Coccoliths have a central area of radiating rods.

Remarks: Identified at stations HC001 at 56m and HC005 at 62m.

Syracosphaera pulchra Lohmann, 1902

Plate 3, Fig. 2.

Winter and Siesser, 1994, pg. 139, Fig. 122.

Kleijne, 1993, pg. 259, Plate 5, Fig. 10.

Andruleit, 1995, Table 4, Figs 6a-b.

Samtleben and Bickert, 1990, Plate 1, Fig. 1.

Description: Round coccosphere with large ovoid coccoliths. Coccoliths have a distinct central are, mainly enclosed with perforations. Some have a central protruding structure. Often associated with a second form of coccolith of inverted cup shape with sunken central area, showing perforations around the rim.

Remarks: This species is readily identified by light and electron microscopes in water and sediment samples. Identified at stations HC001 at 56m, 164m and 218m; HC002 at 28m to 163m; HC004 at 17m, 120m, 180m and 240;, HC005 to 117m; HC007 to 35m; HC009 at 29m; and in most sediment samples including Core GC07 at 140-143cm and 150-153cm.

Syracosphaera rotula Okada and McIntyre, 1977

Winter and Siesser, 1994, pg. 139, Fig. 122.

Kleijne, 1993, pg. 259, Plate 5, Fig. 10.

Description: Round coccosphere covered in coccoliths with radial rods in the central area. The rim of the coccolith is broad and well defined. Often associated with a dimorphic endothecal of large round wheel-like coccoliths.

Remarks: Identified at station HC001 at 56m.

Syracosphaera sp.

Plate 2, Figs 6 and 7.

Description: Round coccospheres with ovoid coccoliths. Coccoliths have a central area of radiating rod structures.

Remarks: A number of coccospheres were identified as belonging to *Syracosphaera* spp. These coccospheres could not be readily identified previously published illustrations and are grouped together as 'Syracosphaera sp.' Members of this group were identified at CTD 16 at 14m, 28m, 103m and 152m; CTD 21 at 29m and 53m; HC001 at 12m, 56m and 218m; HC002 at 55m and 110m; HC004 at 17m, 34m and 62m; and HC005 at 62m, 172m.

Genera incertae sedis

Polycrater galapagensis Manton and Oates, 1980

Winter and Siesser, 1994, pg. 141, Fig. 128.

Description: Coccosphere constructed of tightly packed diamond-shaped cups of solid structure.

Remarks: Identified at station HC005 at 62m.

Umbellosphaera tenuis (Kamptner, 1937) Paasche in Markali and Paasche, 1955

Plate 2, Fig. 3.

Winter and Siesser, 1994, pg. 142, Fig. 132.

Kleijne, 1993, pg. 221, Plate 8, Figs 3-6.

Description: Round coccosphere covered with large circular overlapping coccoliths. The coccoliths have a distinct circular opening at the centre, from which radiate lines of irregular high relief corrugation.

Remarks: This species is readily identified in water and sediment samples using both the electron and light microscopes. It is identified at stations HC001 down to 218m; HC002 to 163m; HC004 to 62m; HC005 to 172m; HC009 to 29m; and, in most sediment samples. The abundance in sediment samples suggests this is not one of the more fragile species subject to dissolution.

Wigwamma antarctica Thomsen in Thomsen et al., 1988

Thomsen et al., 1988, pg. 424, Figs 9-15.

Description: Semi-calcified coccosphere with 'tent-like' coccoliths.

Remarks: Identified in water samples south of the PF (CTD 54) at a depth of 103m.

Wigwamma triradiata Thomsen in Thomsen et al., 1988

Thomsen et al., 1988, pg. 426, Figs 16-20.

Description: Semi-calcified coccosphere with three tent-pole structures protruding from the coccoliths.

Remarks: Identified in water samples south of the PF (CTD 54) at a depth of 103m.

2. Holococcolithophores - coccoliths of hexagonal prisms, rhombohedral crystals, or both.

Family **Coccolithaceae** Poche, 1913

cf. *Coccolithus pelagicus* f. *hyalinus* (Gaarder and Markali, 1956) Kleijne, 1991

Plate 1; Fig. 5.

Winter and Siesser, 1994, pg. 118 Fig. 6.

Kleijne, 1993, pg. 45, Plate 4, Figs 2.

Andruleit, 1995, Table 2, Figs 2a-d

Samtleben and Bickert, 1990, Plate 1, Fig. 8, Plate 2, Fig. 9.

Description: The motile stage of *C. pelagicus*, resembling a holoccocolithophorid.

Remarks: The identification of this coccosphere is not certain in this study and may be an unidentified holococcosphere. One coccosphere was identified at station HC001 at a depth of 12m.

Genera incertae sedis

Calicasphaera diconstricta (Halldal, 1953) Heimdal in Heimdal and Gaarder, 1980.

Winter and Siesser, 1994, pg. 143, Fig. 140.

Kleijne, 1993, pg. 38, Plate 1, Figs 1-4.

Description: Coccosphere with round cup-like coccoliths with distinct, thickened rims.

Remarks: This species was identified at station HC009 at 14m.

Calyptrolithophora papillifera (Halldal, 1953) Heimdal in Heimdal and Gaarder, 1980

Winter and Siesser, 1994, pg. 150, Fig. 172.

Kleijne, 1993, pg. 67, Plate 12, Figs 1-2.

Description: Round coccosphere constructed of oval coccoliths of uniform sieve-like structure. Rims of coccoliths are slightly thickened and raised.

Remarks: This species was identified at HC001 at 12m water depth.

Corisphaera gracilis Kamptner, 1937

Winter and Siesser, 1994, pg. 151, Fig. 174.

Kleijne, 1993, pg. 67, Plate 12, Figs 3-5.

Description: Round coccosphere with oval coccoliths. Coccoliths are basket-like with 2 to 3 rows of crystal around the edge and a raised 'bridge' across the centre made of the same crystal structures.

Remarks: This species was identified at station HC009 at 29m.

Sphaerocalyptra quadridentata (Schiller, 1913) Deflandre, 1952.

Winter and Siesser, 1994, pg. 154, Fig. 187.

Kleijne, 1993, pg. 78, Plate 17, Fig. 3.

Description: An irregular shaped coccospheres with coccoliths resembling small peaked hats. Coccoliths are rounded with small peaks at the distal point.

Remarks: One coccosphere was identified at station HC005 at 62m water depth.

Zygospheara hellenica Kamptner, 1937.

Winter and Siesser, 1994, pg. 155, Fig. 190.

Kleijne, 1993, pg. 84, Plate 18, Figs 3-5.

Description: Coccosphere of ovoid coccoliths of uniform crystal shape and size. The outer rim of the coccolith is more calcified as is the central, larger crystal.

Remarks: This species was identified at station HC009 at depths down to 109m.

Zygosphaera marsilii (Borsetti and Cati, 1976) Heimdal, 1962.

Winter and Siesser, 1994, pg. 155, Fig. 191.

Kleijne, 1993, pg. 84, Plate 18, Fig. 6.

Description: The coccoliths on this coccosphere show crystals arranged in circular lines around the ovoid coccolith, accompanied by a central arch across the width of the coccolith constructed from two rows of crystals.

Remarks: This species was identified at station HC009 at a depth of 29m.

Holococcolithophorid spp

Remarks: A number of holococcolithophorids spp were identified at stations HC001 at depths of 12m and 110m; HC005 at depths down to 62m; and, HC007 at 35m. The identification of these species is uncertain due to their poor state of preservation and can not be correlated to previously published photographs.

B. Coccolithophores identified in the sediments only

Family **Ceratolithaceae** Norris, 1965

Ceratolithus cristatus Kamptner, 1950 var. *cristatus*

Perch-Nielsen, 1985, pg. 455, Fig. 2.

Sato and Takayama, 1992, pg. 459, Fig. 5b.

Okada, 1992, Plate 1, Fig. 30.

Description: Horse-shoe shaped coccolith.

Remarks: This single coccolith was identified by light microscope in Core GC07 at 310-313cm.

Family **Coccolithaceae** Poche, 1913

Calcidiscus macintyrei (Bukry and Bramlette, 1969) Loeblich ad Tappan, 1978.

Plate 5, Fig. 1.

Perch-Nielsen, 1985, pg. 465, Fig. 4., pg. 462, Figs 7-8.

Sato and Takayama, 1992, pg. 459, Fig. 5a,b.

Takayama and Sato 1987, Plate 1, Fig. 8.

Description: A large round coccolith of two separate shields, both of which display a radial pattern from the centre.

Remarks: This coccolith is very similar to *C. leptoporus*, although larger with more segments on the distal shield. It is easily recognised in sediments using the light microscope where the radiation is obvious, as are the two shields. This species has a biostratigraphic range from the Early Miocene to Early Pleistocene and is a component of re-worked sediment samples.

Coccolithus pelagicus (Wallich, 1877) Schiller, 1930 f. *pelagicus*

Perch-Nielsen, 1985, pg. 465, Figs 1-4.

Winter and Siesser, 1994, pg. 119, Fig. 11B.

Andruleit, 1995, Table 2, Figs 1a-d.

Tanaka, 1991, Plate 2, Fig. 18.

Description: Large, oval coccoliths overlapping on coccosphere. Coccoliths constructed of two shields with pronounced sunken central area on distal shield with many radial elements.

Remarks: This species was absent from water column samples but identified in all sediment samples using both the light microscope and electron microscope.

Oolithus fragilis (Lohmann, 1912) Martini and Müller, 1972 var. *fragilis*

Okada, 1992, Plate 1, Fig. 11.

Plate 2, Fig. 2.

Description: Round coccolith with distinct bio-refringence pattern, with a faint radial pattern and a small bright central area of four fan shapes.

Remarks: This coccolith was identified in sediment samples using the light microscope. Plate 2, Figure 2 was initially identified as the proximal plate of *C. leptoporus* and re-named to *O. fragilis* following advice from Okada (pers com).

cf. *Umbellosphaera angustiforamen* Okada and McIntyre 1977.

Perch-Nielsen, 1985, pg. 465, Fig. 5.

Description: Large slightly ovoid ring with distinct sections divided by zigzag lines.

Remarks: This species was identified by electron microscope in surface sediment samples of Cores GC20, GC31 and GC32.

Umbilicosphaera sibogae (Weber-Van Bosse, 1901) Gaarder, 1970 var. *sibogae*

Perch-Nielsen, 1985, pg. 462, Figs 3-4.

Okada, 1992, Plate 1, Fig 13.

Tanaka, 1991, Plate 2, Figs 1-2, 5-6.

Description: Circular coccoliths. Distal shield is divided into segments and has a distinct circular central opening. The proximal shield is off centre to the distal shield.

Remarks: This species was identified in sediment samples only using both light and electron microscopes. The light microscope image is distinct, with a large well defined central opening.

Family **Discoasteraceae** Tan, 1927

Discoaster sp. Tan, 1927

Plate 5, Fig. 5.

Description: Coccolith with star shaped form.

Remarks: This coccolith was identified in Core GC31 at 75-78cm.

Family **Helicosphaeraceae** Black, 1971, emend. Jafar and Martini, 1975

cf. *Helicosphaera sellii* Bukry and Bramlette, 1969

Perch-Nielsen, 1985, pg. 491, Figs 23-24, 26.

Takayama and Sato 1987, Plate 4, Figs 4a-b.

Sato and Takayama, 1991, Figs 6a-b.

Description: Coccolith with 'H' like appearance. Central area has two definite openings which are offset at an angle.

Remarks: This species is distinguished from *H. carteri* by the central area which is readily identified using the light microscope. This coccolith was identified in Core GC07 at 110-113cm.

Family **Noelaerhabdacea** Jerkovic, 1970

Cyclicargolithus floridanus (Roth and Hay in Hay et al., 1967) Bukry, 1971

Takayama and Sato 1987, Plate 3, Fig. 2.

Wei and Thierstein, 1991, Plate 2, Figs 5-9.

Perch-Nielsen, 1985, pg. 506, Figs 13-14.

Description: This coccolith has a pattern of four, broad-shaped fans, with a distinctive central ring, comprising the base of the four 'fans'.

Remarks: This genus is designated to Family Prinsiaceae Hay and Mohler 1967, by Perch-Nielsen (1985). However, to be consistent with the newer classification system of Jordan and Kleijne, 1994, it

placed in the Family Noelaerhabdacea. This species was identified in a number of sediment samples including GC07, 51-52cm. The coccolith is completely circular as distinct from the sub-circular shape of *Reticulofenestra* spp It has a biostratigraphic range between Early Miocene to Late Pliocene, indicating reworked older material in Core GC07.

Gephyrocapsa caribbeanica Boudreaux and Hay, in Hay et al., 1967

Winter and Siesser, 1994, pg. 123, Fig. 36.

Samtleben and Bickert, 1990, Plate 1, Fig. 14.

Plate 4, Fig. 8; Plate 5, Fig. 4.

Description: Medium sized gephyrocapsid with central area almost enclosed.

Remarks: This species was identified in the sediments samples only and easily distinguished using both light and electron microscopes. The coccolith size varies between 3 and 6µm.

Gephyrocapsa oceanica Kamptner, 1943

Winter and Siesser, 1994, pg. 123, Fig. 37.

Kleijne, 1993, pg. 253, Plate 2, Fig. 5.

Andruleit, 1995, Table 3, Figs 3a-c.

Samtleben and Bickert, 1990, Plate 1, Fig. 12.

Description: A large gephyrocapsid with almost circular coccoliths showing a large central opening covered with a grill-like structure and surrounded by a distinct, thickened rim. The bridge of two overlapping elements is almost horizontal across the width of the central opening.

Remarks: This species is easily identified under light microscope due to the prominent rim around the central opening and the angle of the central bridge. Coccoliths are larger than 5µm.

Small *Gephyrocapsa* spp

Plate 5, Fig. 4.

Description: Coccoliths are very small with a size range of 1 to 2.5µm.

Remarks: Coccoliths of this type were identified in sediment samples but could not be identified at species level. The main reference was from a light microscope slide of small *Gephyrocapsa* acme supplied by Dr J. Giraudeau from the University of Bordeaux.

Pseudoemiliania lacunosa (Kamptner, 1963) Gartner, 1969

Plate 5, Fig. 4.

Perch-Nielsen, 1985, pg. 512, Fig. 62; pg. 514, Figs 2-5.

Sato and Takayama, 1992, pg. 459, Fig 2a.

Takayama and Sato, 1987, pg.. 697, Fig. 7a.

Description: Circular coccolith with large, four sided central opening and four rounded sides with visible striation on outer rims.

Remarks: This genus is designated to Family Prinsiaceae Hay and Mohler 1967, by Perch-Nielsen (1985). However, to be consistent with the newer classification system of Jordan and Kleijne, 1994, it is placed in the Family Noelaerhabdacea. This species is easily identified by light microscope in sediment samples.

Reticulofenestra spp

Remarks: *Reticulofenestra* spp were common throughout the sediment samples and where possible, were categorised by size and closed or open central opening. Three main sizes were identified, large (6 -12µm), medium (5 - 8µm) and small (3 - 5µm). A number of specimens were difficult to categorise and are placed in the group '*Reticulofenestra* sp.'

Reticulofenestra gelida (Geitzenauer, 1972) Backman, 1978

Perch-Nielsen, 1985, pg. 514, Fig. 65, pg. 506, Fig. 8.

Wei and Thierstein, 1991, Plate 1, Figs 1-4.

Plate 5; Fig. 7.

Description: Large coccolith between 6 to 12µm with closed central area. Under light microscope the central opening forms a small square, with the four lobes in close association divided by lines.

Remarks: This species was frequent in the sediment samples.

Reticulofenstra pseudoumbilica (Gartner, 1967) Gartner 1969

Takayama and Sato 1987, Plate 3, Figs 4a-b.

Perch-Nielsen, 1985, pg. 506, Fig. 59.

Description: Large coccolith between 6 to 12μm with a large open central area clearly distinguished by light microscope as a square shape. The four lobes are completely separate, similar to *P. lacunosa*, but larger, brighter and have no striation.

Remarks: This species was common in the sediment samples.

Reticulofenestra sp.

cf. *Reticulofenestra productella* (Bukry 1973) Gallagher 1989.

Reticulofenestra antarctica Haq 1976

Description: Medium semi-circular coccoliths approximately 5 - 8μm with small or closed central area.

Remarks: The size range for this species and the closed central area agrees with the descriptions for *R. antarctica* and *R. perplexa* (Perch-Nielsen, 1985; Beaufort, 1992), both Miocene species, and *R. productella* (Beaufort, 1992), a Pleistocene species. As *R. perplexa* is more ovoid than semi-circular (Wei and Thierstein, 1991; Plate 1) it is exclude as a possibility.

Reticulofenestra sp.

cf. *Reticulofenestra minutula* (Gartner, 1967) Haq and Berggren, 1978

Description: Medium coccoliths approximately 5 - 8μm with an open central area.

Remarks: The size of this species is in agreement with *R. minutula* (Pliocene) and *R. haqii* (Miocene and Pliocene). The central opening is of good size suggesting this species is *R. minutula* rather than *R. haqii* which has a smaller opening (Perch-Nielsen, 1985; Beaufort, 1992).

Reticulofenestra sp.

Description: Small coccolilths 3 - 5μm with a closed central area.

Remarks: These coccoliths are most likely the small end members of *R. antarctica* and *R. productella* described above and are too big to be considered as *R. minuta* which is <3μm. These coccoliths were uncommon in the sediment samples.

Family **Pontosphaeraceae** Lemmermann, 1908

Pontosphaera sp.

Description: Large oval coccolith with distinct perforation of central area.

Remarks: This species was difficult to identify at species level, although the perforations were larger rather than fine and is very similar to *Pontosphaera* sp. illustrated by Perch-Nielsen (1985; Fig. 52, no. 28). identified in sediment samples of GC07 at 42-43cm; 90-93cm; 100-103cm; 110-113cm; 140-143cm; 150-153cm; and 160-163cm.

Family **Rhabdosphaeraceae** Ostenfeld, 1899

Acanthoica sp.

Description: Single rhabdoliths forming long thin spines, identical to the rhabdoliths identified for *A. quattrospina.*

Remarks: This coccolith was identified in the sediments of GC07, at the depths of 20-23cm and 30-33cm using an electron microscope. It is most likely they belong to the species *A. quattrospina.*

Rhabdosphaera clavigera Murray and Blackman, 1898, var. *clavigera*

Plate 4, Fig. 6.

Takayama and Sato, 1987, pg. 698, Fig. 9.

Okada, 1992, Plate 1, Fig 25.

Tanaka, 1991, Plate 2, Figs 13, 16.

Perch-Nielsen, 1985, pg. 516, Figs 30, 31.

Description: Single coccoliths with long spine thickening towards one end into a club shape and flattening out to a convex disc at the opposite end.

Remarks: This species is distinguished from R. stylifera by the thinner spine. This species was a common component of sediment samples.

Family **Sphenolithaceae** Deflandre, 1952

Sphenolithus sp.

Description: Coccolith with distinct bio-refringence pattern, with four section forming rough triangle shapes, where one section is considerably larger than the others.

Remarks: This species was identified in a few sediment samples including GC07 at 270-273cm.

Reworked spp

A number of coccoliths were grouped together as 'reworked spp'. Where possible these species were identified, i.e., *C. floridanus*, *C. macintyrei* and *Reticulofenestra* spp. The remainder are placed in the 'reworked spp' group and are considered to be mostly reticulofenestrids, altered through mechanical breakage and dissolution, precluding positive identification.